Cooling and Feedback in Early-Type Galaxies (and Groups)

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X-ray emission from early-type galaxies = hot gas + stars + LMXBs

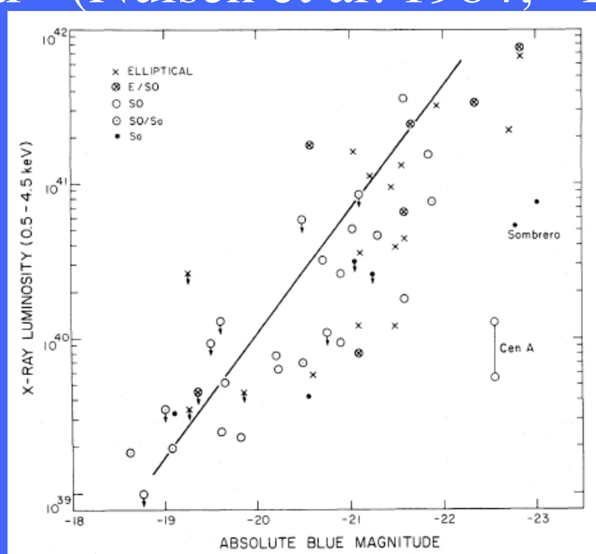
- Heating by radio lobes (e.g. Cen A)
- Results from a Chandra survey of ~160 galaxies -
  30% of very luminous galaxies have cavities;
  80% have X-ray emission from the nucleus
- AGN outbursts heat and remove gas (e.g. NGC1316)
- Is non-thermal pressure support important?

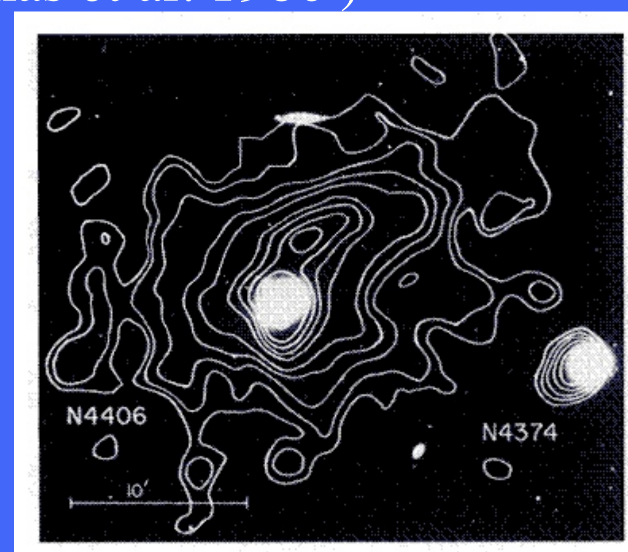
Hot Gas in Early-type Galaxies - The Einstein Era

Prior to Einstein observations, early type galaxies were considered to be gas free, with the gas from stellar mass loss removed by SN driven winds.

Einstein observations showed extended, ~1 keV gas halos with gas masses up to 10^{10} M_{sun}, Strong correlation of L_X and L_B but much scatter. (e.g. Forman et al. 1979, 1985, Canizares et al. 1986)

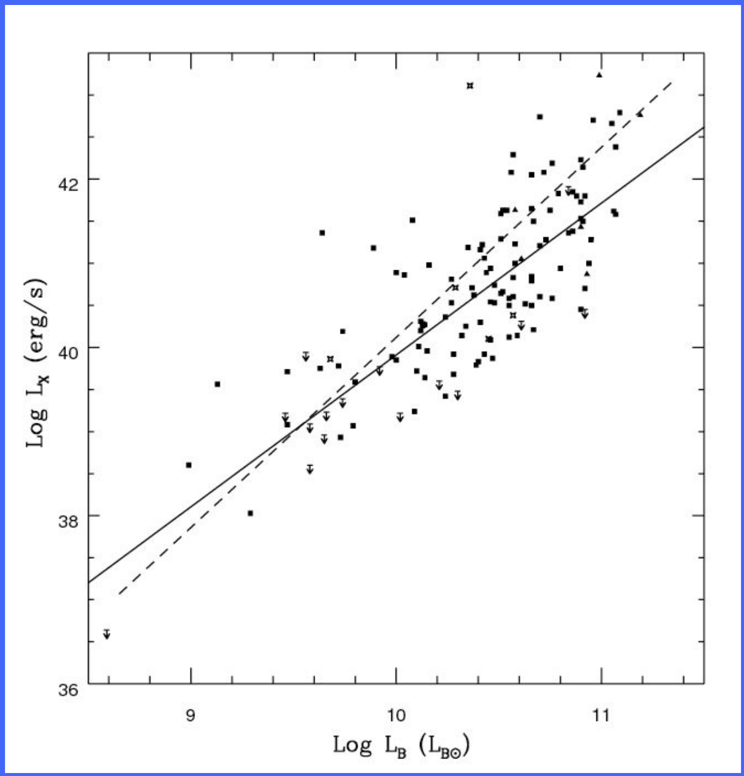
High central gas densities => short cooling times and infall rates of 0.02-3 M_{sun}/year (Nulsen et al. 1984, Thomas et al. 1986)

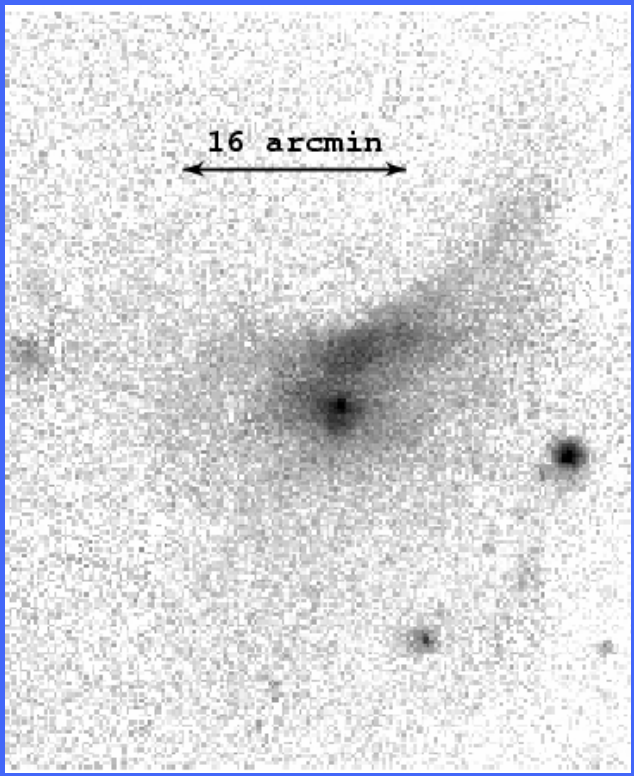




Hot Gas in Early-type Galaxies - The ROSAT Era

Large ROSAT surveys - 293 galaxies (Beuing et al. 1999); 401 galaxies (O'Sullivan et al. 2001) -low temperature systems have reduced gas fraction

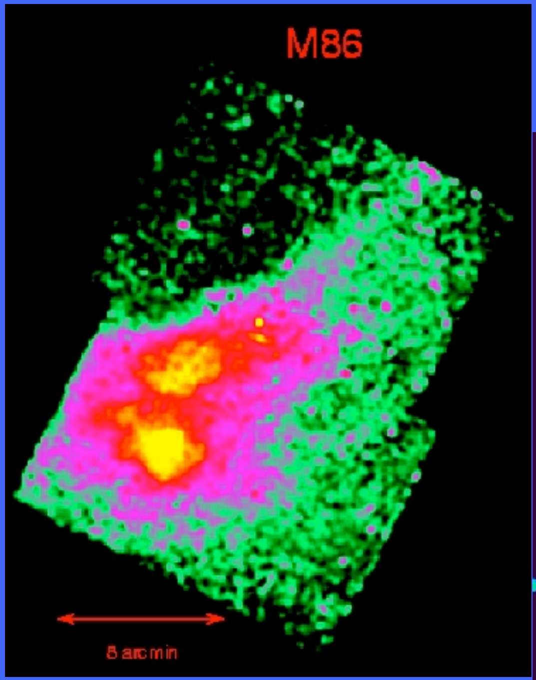


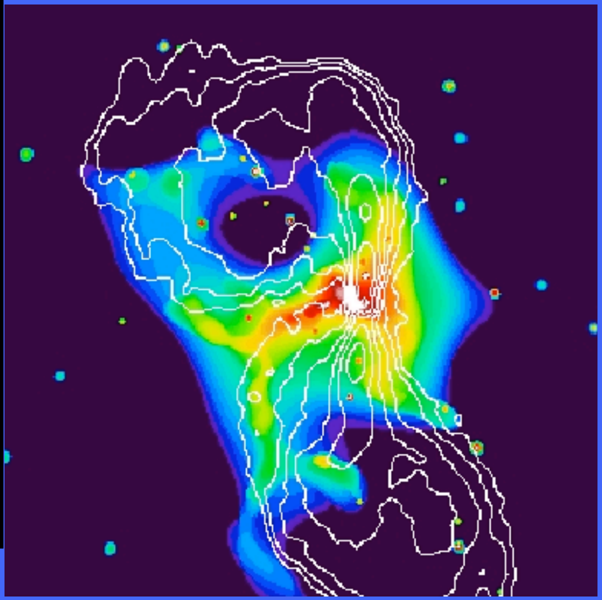


Hot Gas in Early-type Galaxies
- The Chandra - XMM-Newton Era

High spatial resolution shows evidence of AGN outbursts -

- cavities,
- shocks/ripples
- jets,
- nuclear emission

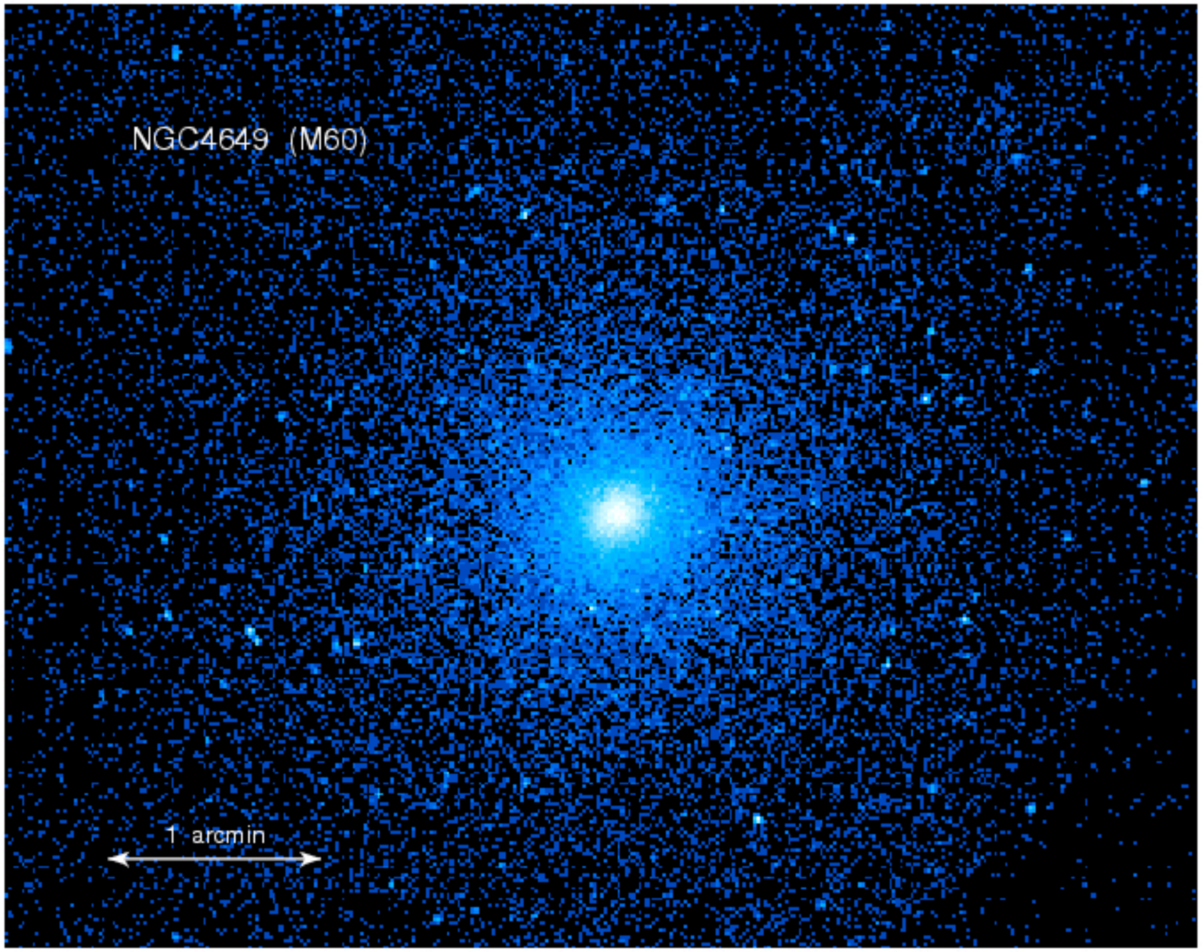




M84 X-ray + Radio Contours

(Finoguenov & Jones 2001)

NGC4649 A normal elliptical in Virgo

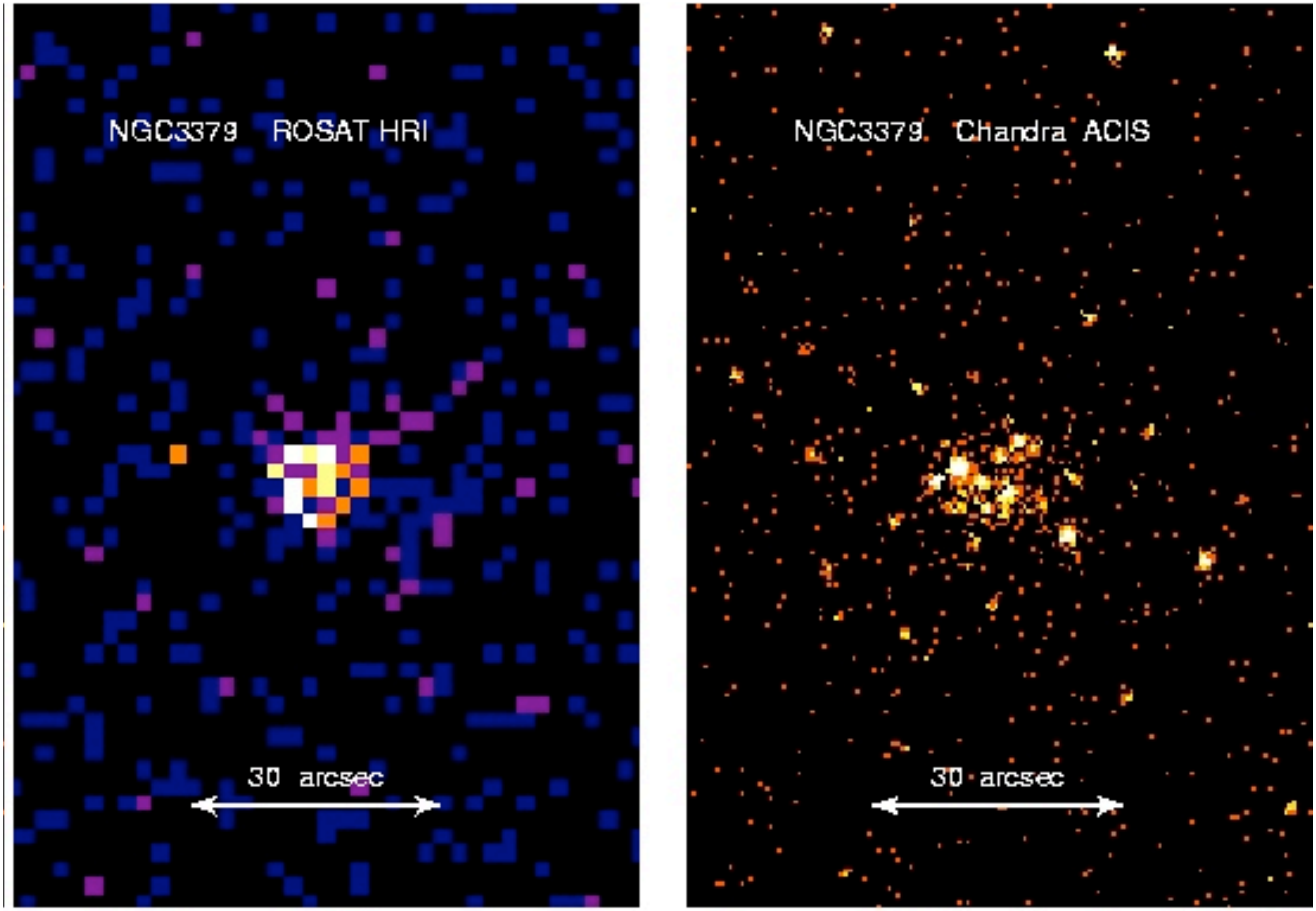


Chandra ACIS-S

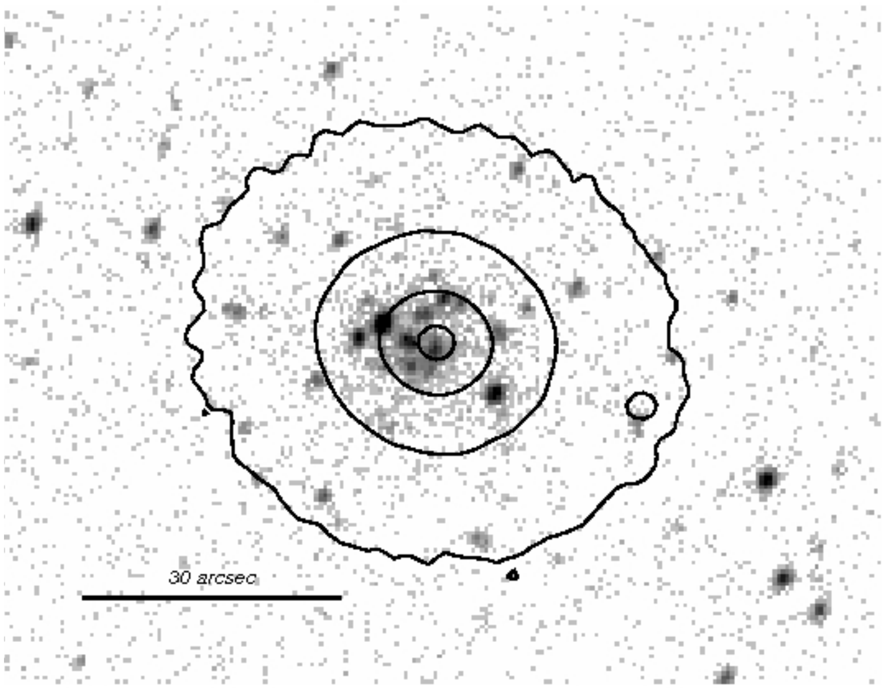
As expected -- Hot ISM

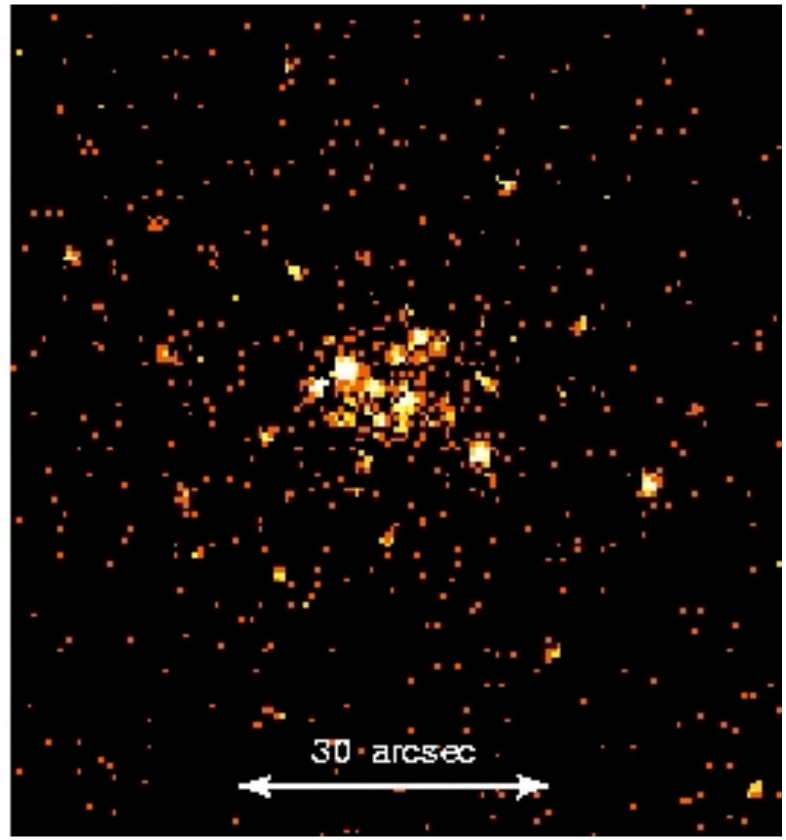
and binary X-ray sources

With Chandra resolution, X-ray emission can be untangled into stars, LMXBs and hot gas



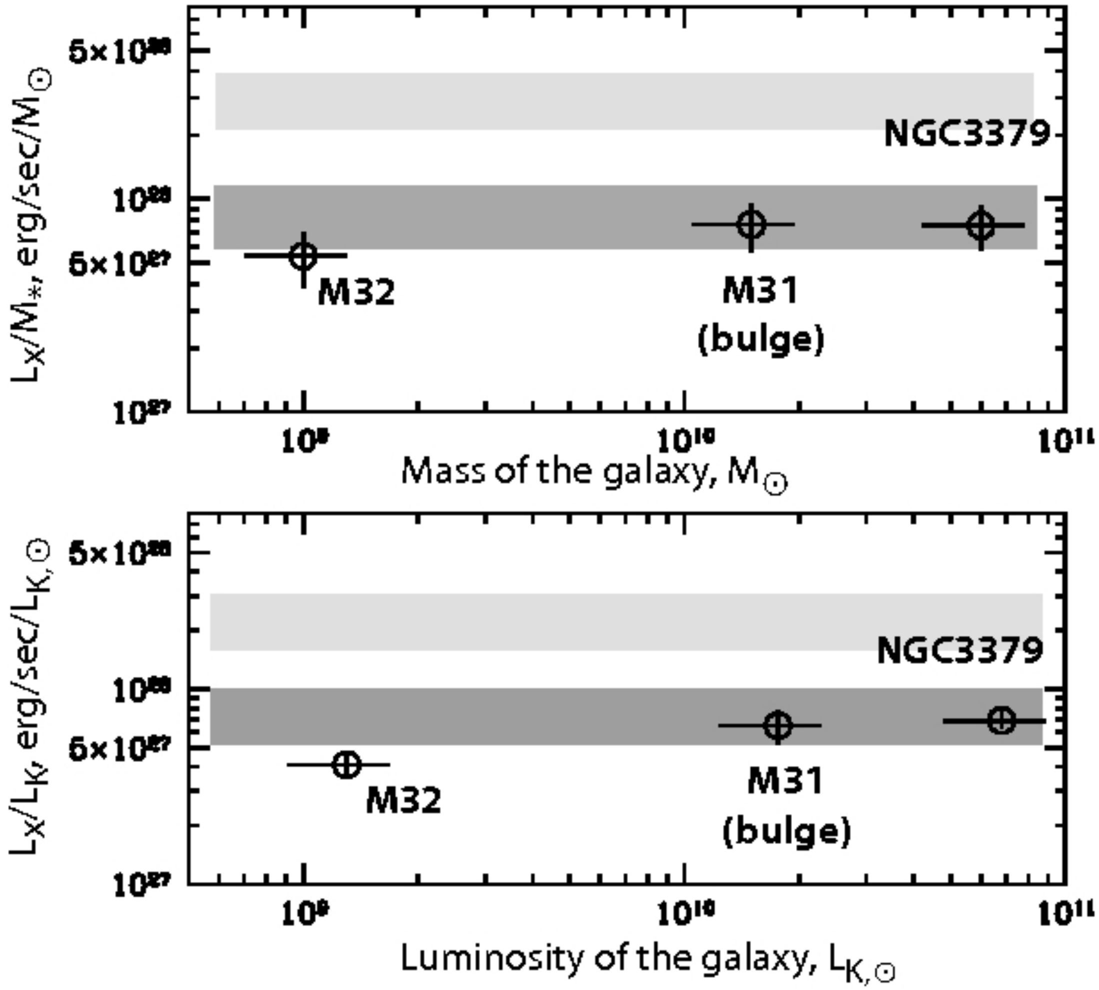
Chandra can resolve bright LMXBs





NGC3379 - Revnivtzev et al

Unresolved X-ray emission in low mass early-type galaxies

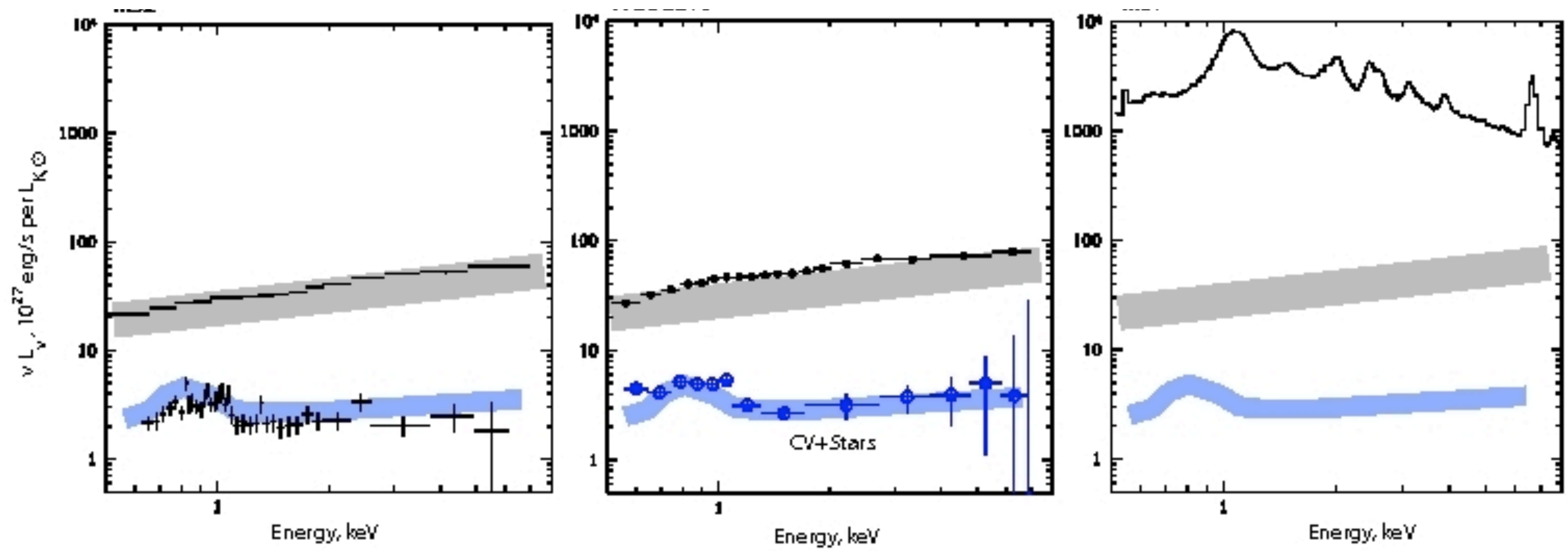


Unresolved X-ray emission is constant per unit stellar mass (top) and per unit K-band luminosity(bottom)

Revnivtzev et al A&A 2008

Use X-ray spectrum to decompose emission

M32 (dwarf) NGC3379 M87



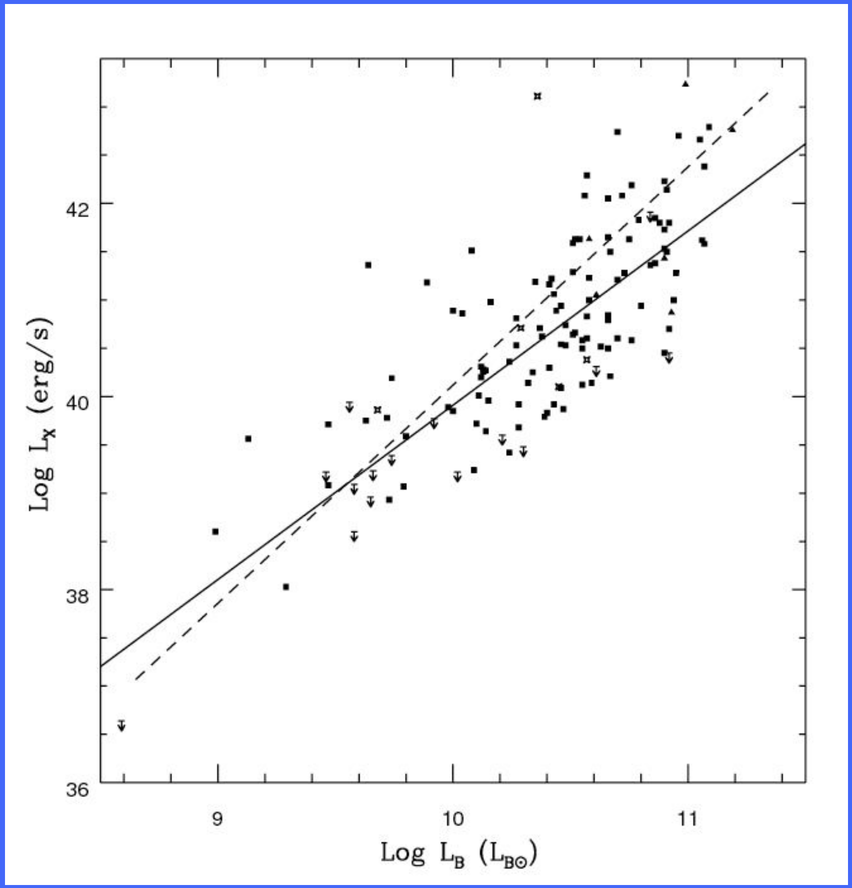
Spectra normalized to K-band luminosity

Upper gray stripe is LMXBs (Gilfanov 2004)
Lower blue stripe is stars

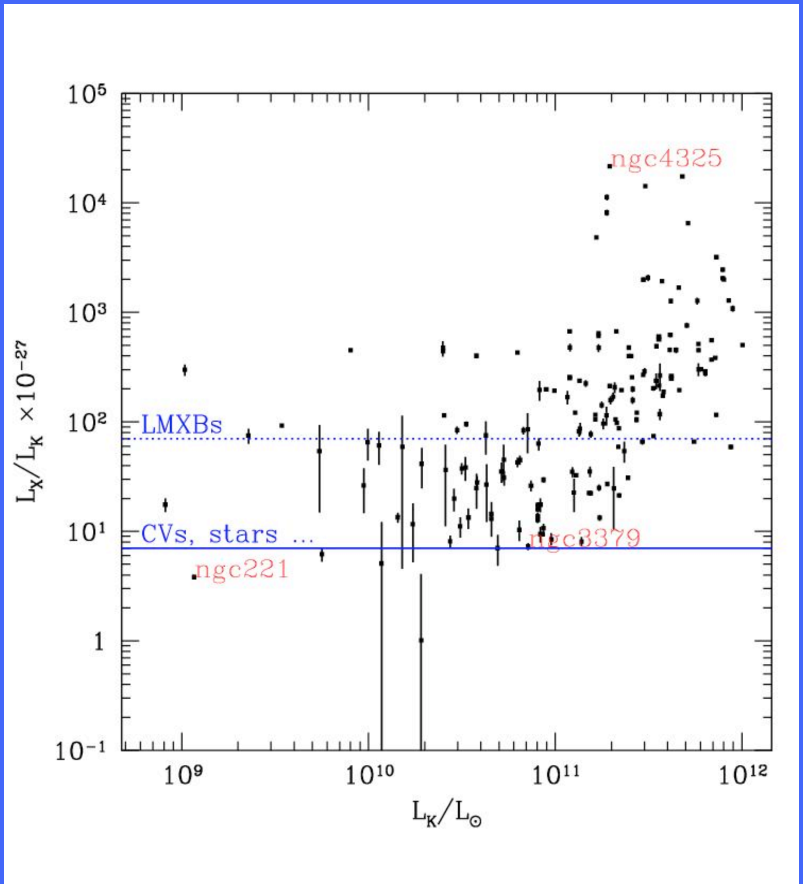
Revnivtzev et al A&A 2008

Hot Gas, Stars & LMXBs in Early-type Galaxies

In luminous ellipticals, most of the X-ray emission is from hot gas, but in the low mass ellipticals, most of the emission is stars and LMXBs



ROSAT (O'Sullivan et al 2001)

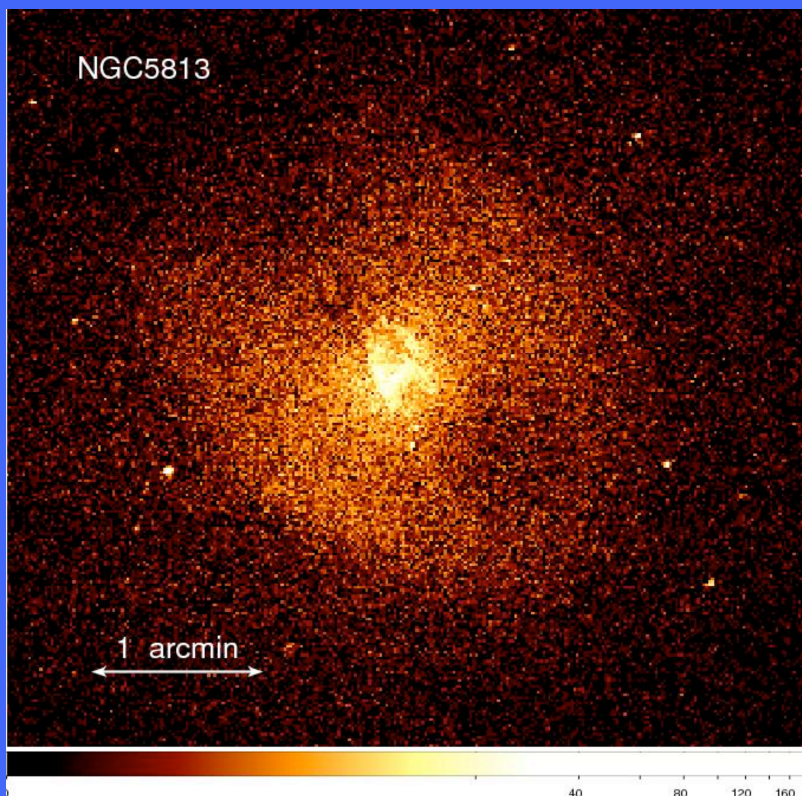


Chandra (Revnivtsev et al.)

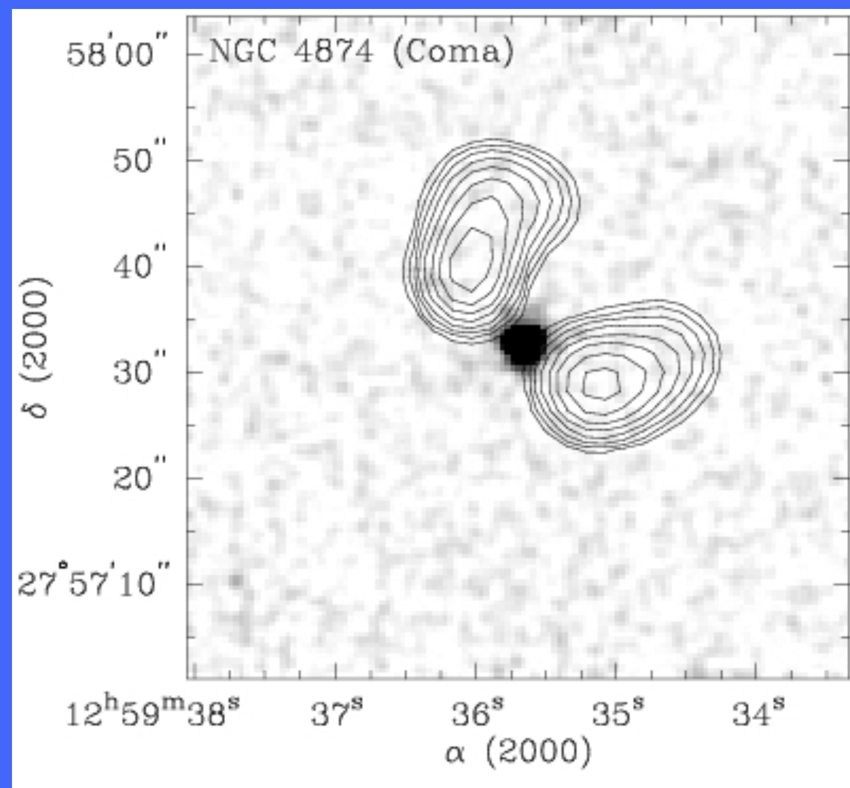
Galaxies with Hot X-ray Coronae

AGN outbursts -- cavities and rising bubbles, shocks

Turbulence and non-thermal pressure support?

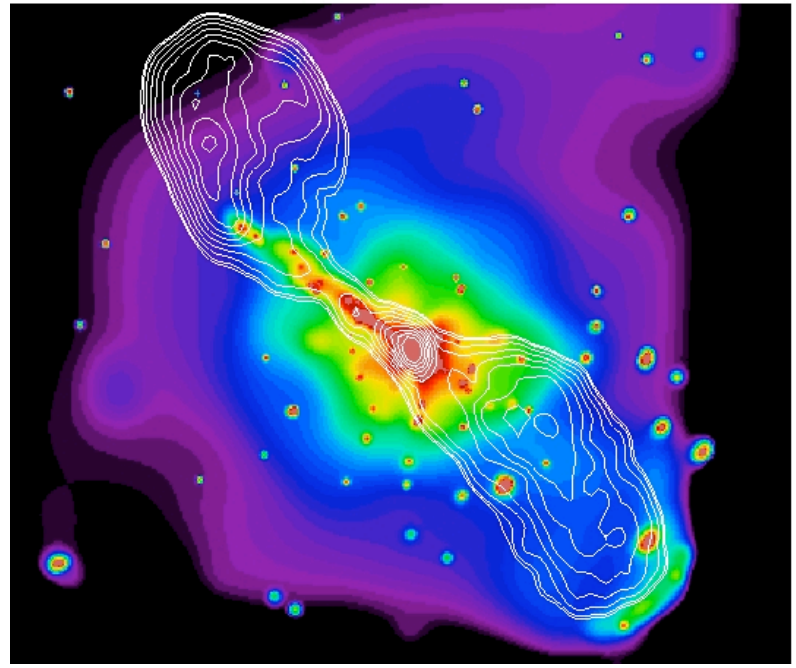


Multiple outbursts in N5813



X-ray and radio emission Sun et al. 2004

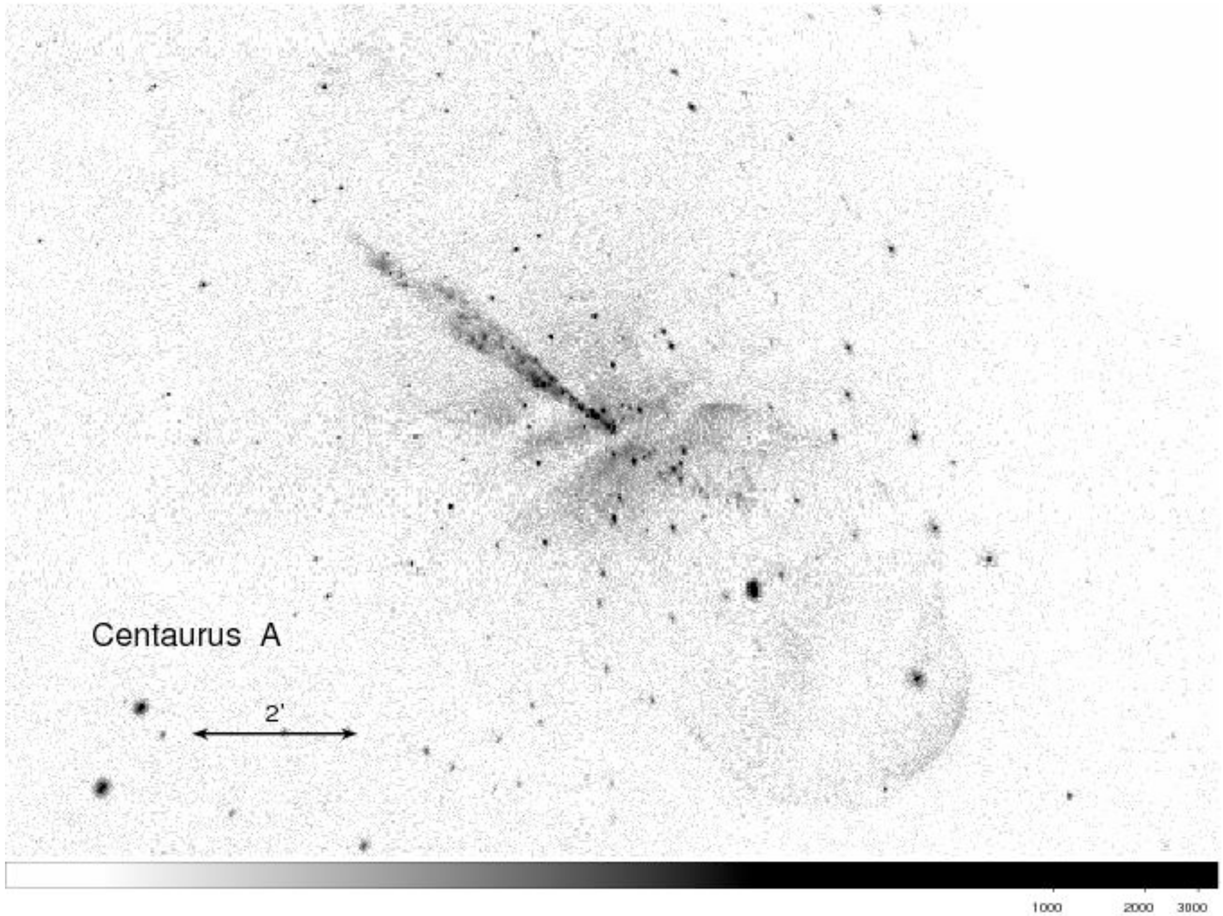
Centaurus A – Bubbles and Jets



Bubble diameter 3 kpc

- Nearest active galaxy (3.4 Mpc; 1''=17pc); Merger with gas rich galaxy
- 250 X-ray point sources + nucleus + jet + knots
- X-ray jet with opposing bubble
- Diffuse emission – kT=0.3 keV – typical for "faint" galaxy
- Radio contours show interaction of radio plasma and origin of bubble

Centaurus A – Bubbles and Jets

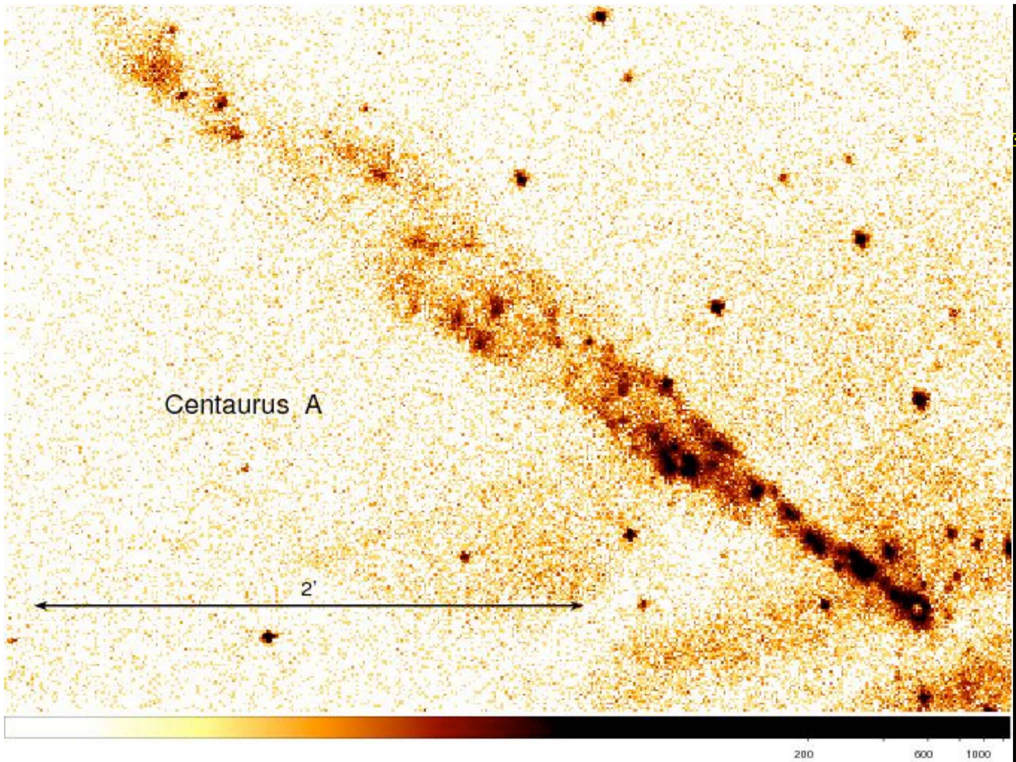


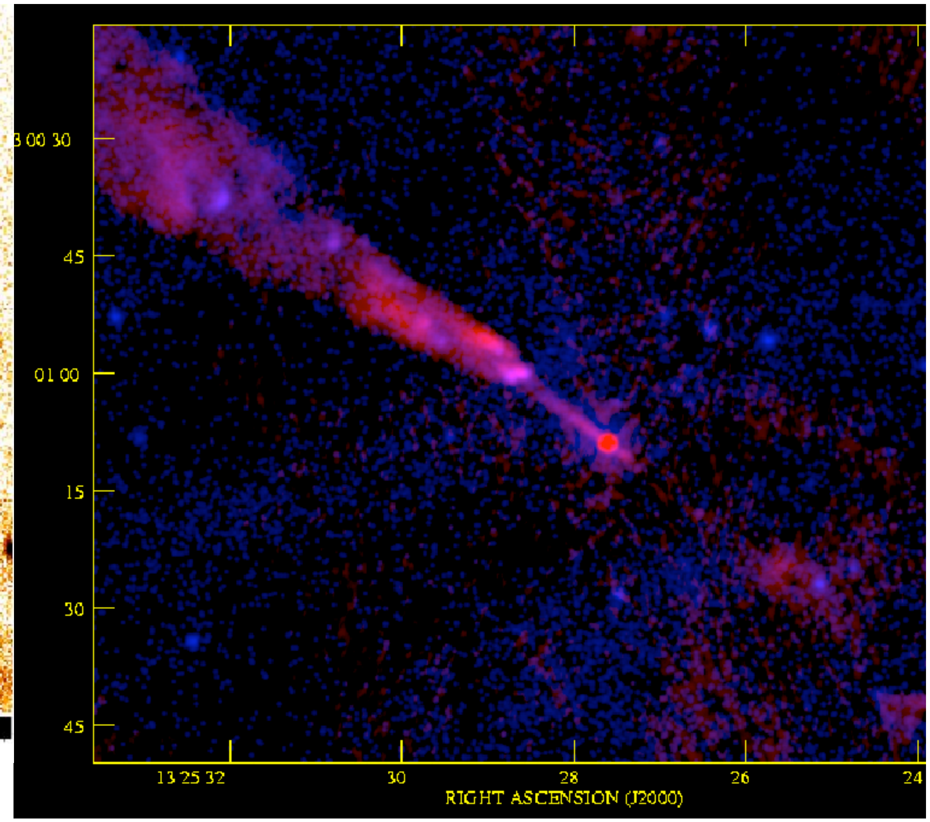
Bubble diameter 3 kpc

Deep (600 ksec) Chandra observation (PI Kraft)

- Diffuse emission – kT=0.3 keV , jet, counter-jet , lobes
- Absorption lanes

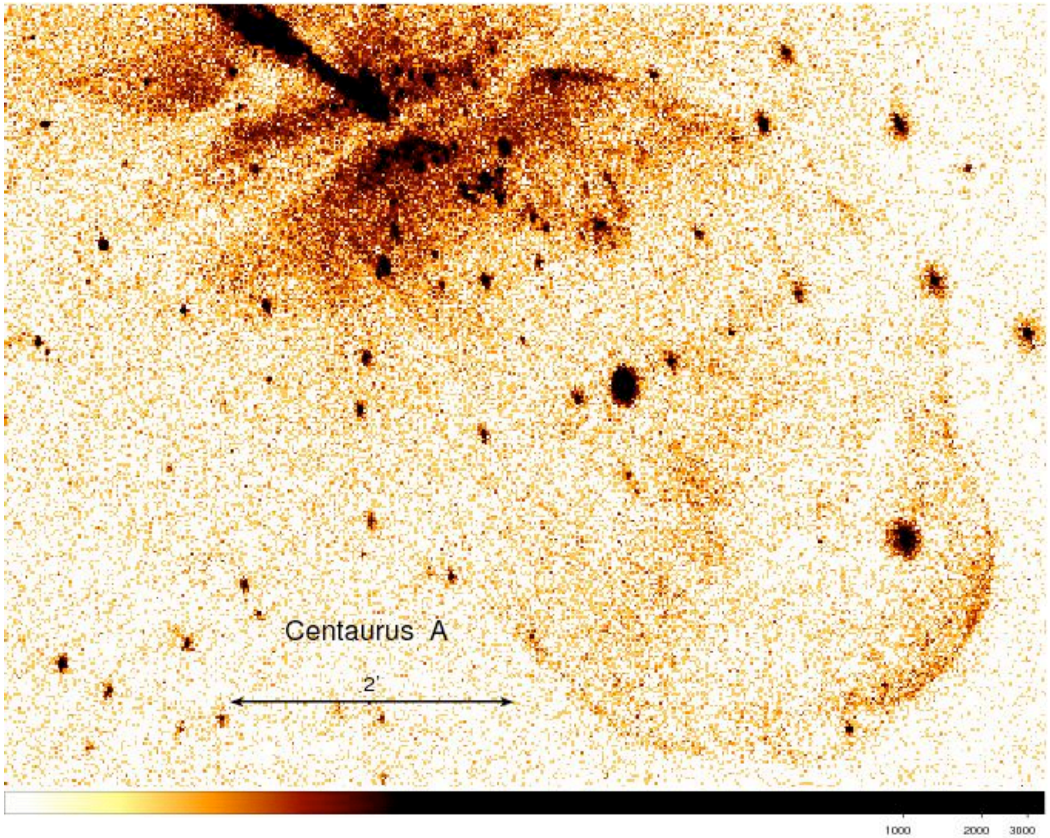
The Jet in Centaurus A





Many X-ray (blue) knots correspond to radio (red) knots (Hardcastle et al. 2003)

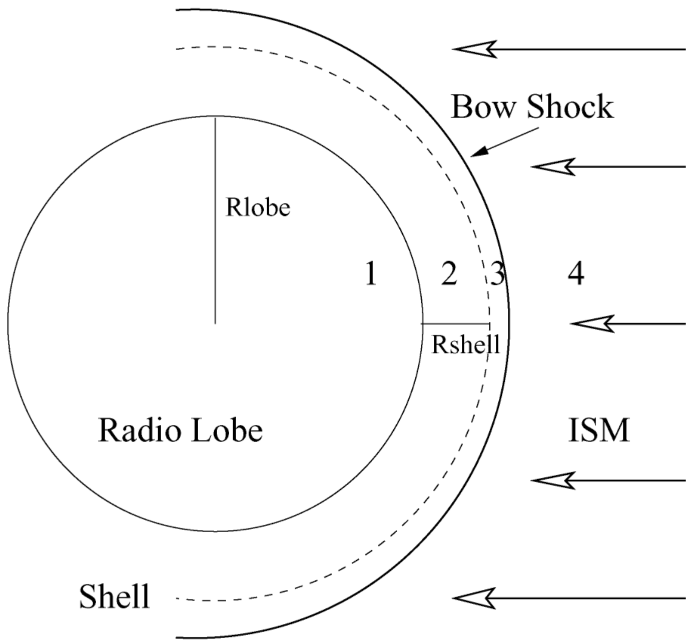
Centaurus A – Bubbles and Jets

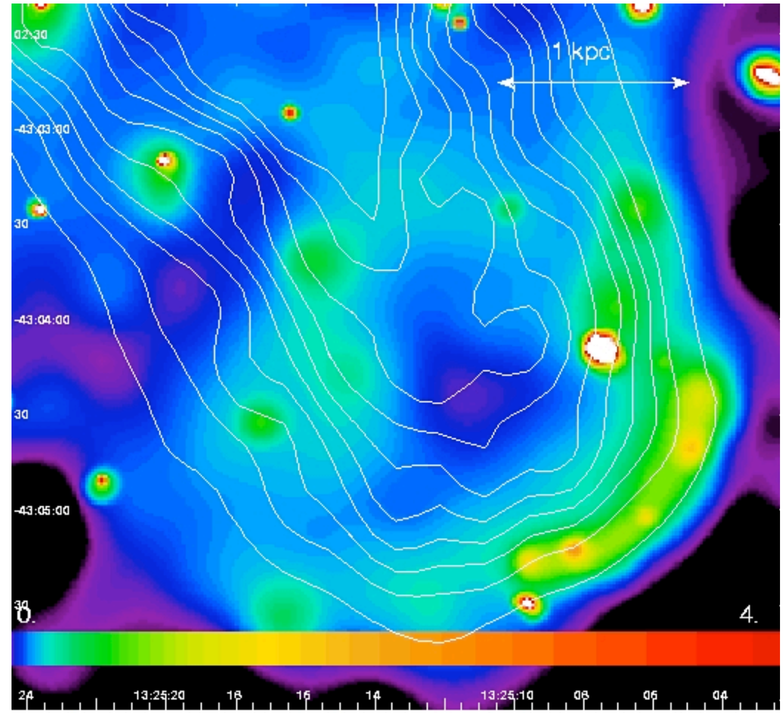


Bubble diameter 3 kpc

- Counter-jet
- Southern lobe - sharp, smooth

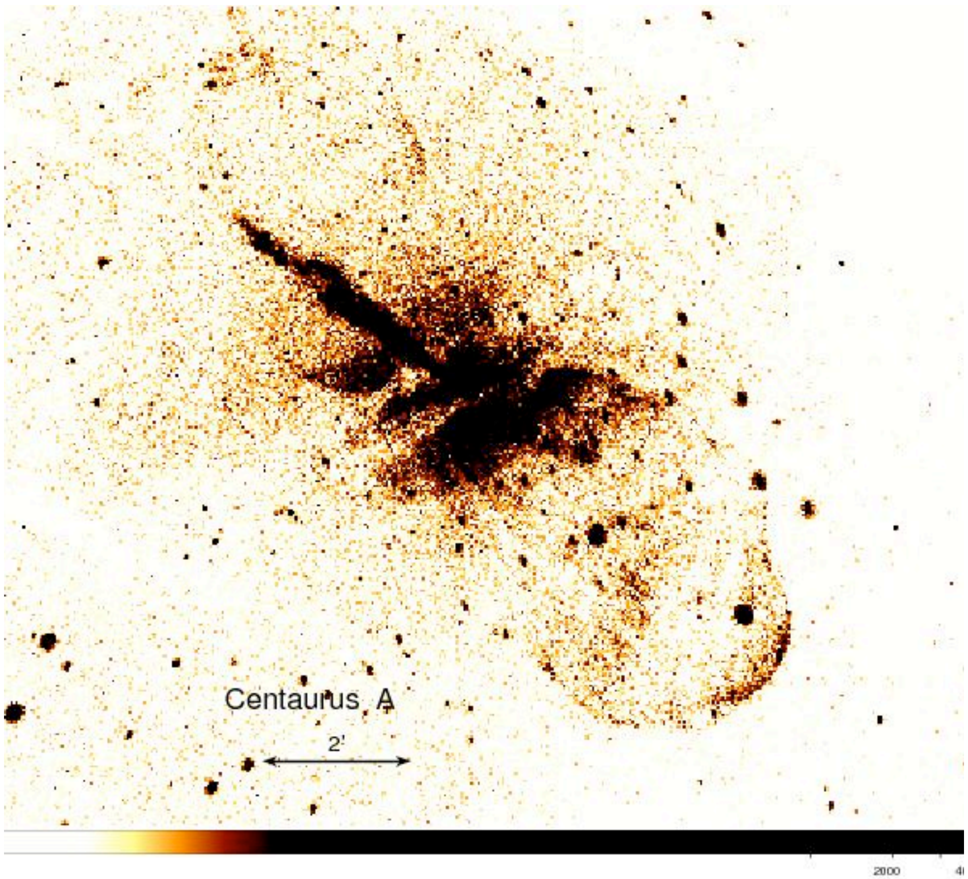
Centaurus A - Southwest Radio Lobe

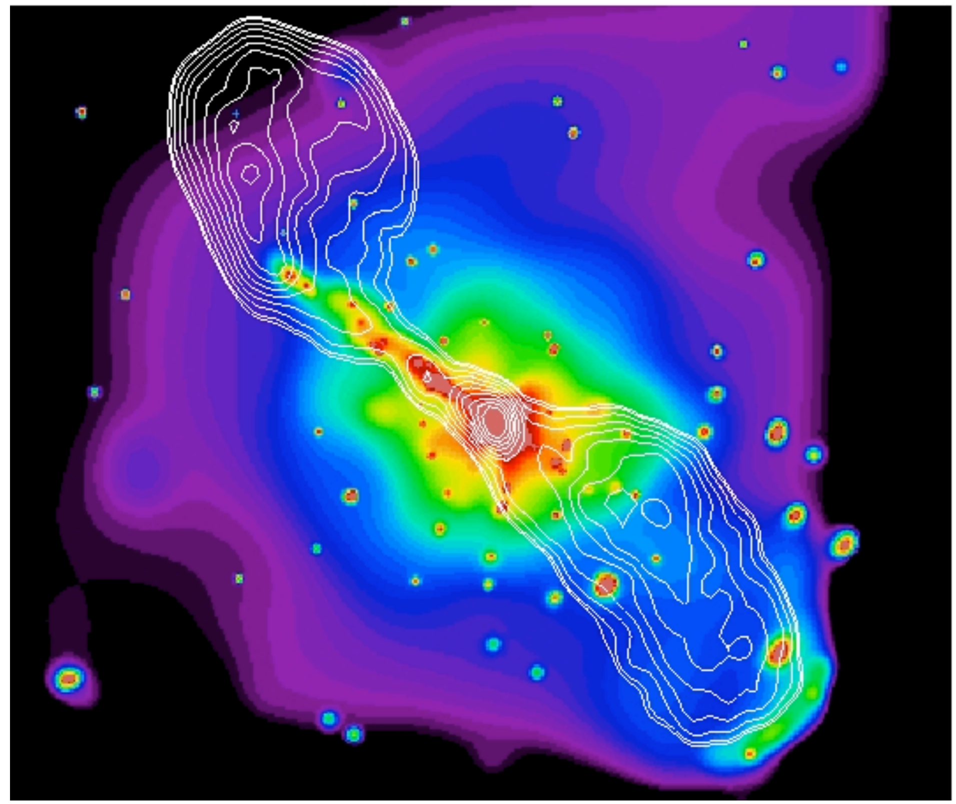




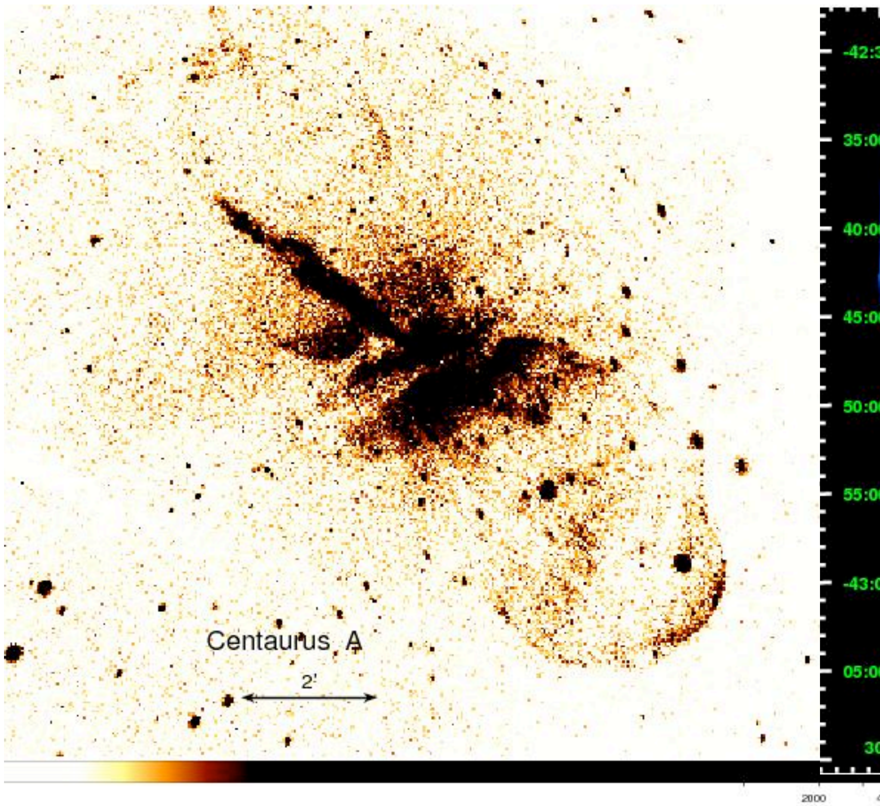
- •Model X-ray bubble as driven by expansion of radio plasma
- •Gas temperature in lobe ~2.9 keV (in ISM kT = 0.3 keV)
- •Shell gas density 2 10^{-2} cm^{-3} (In ISM ~ 2 10^{-3} cm^{-3})
- •Shell overpressured (2 10^{-10} dyn cm^{-2}; in ISM ~10^{-12}, in lobe ~10^{-11})
- •Bubble expanding supersonically at Mach 8.5 (2400 km/sec)

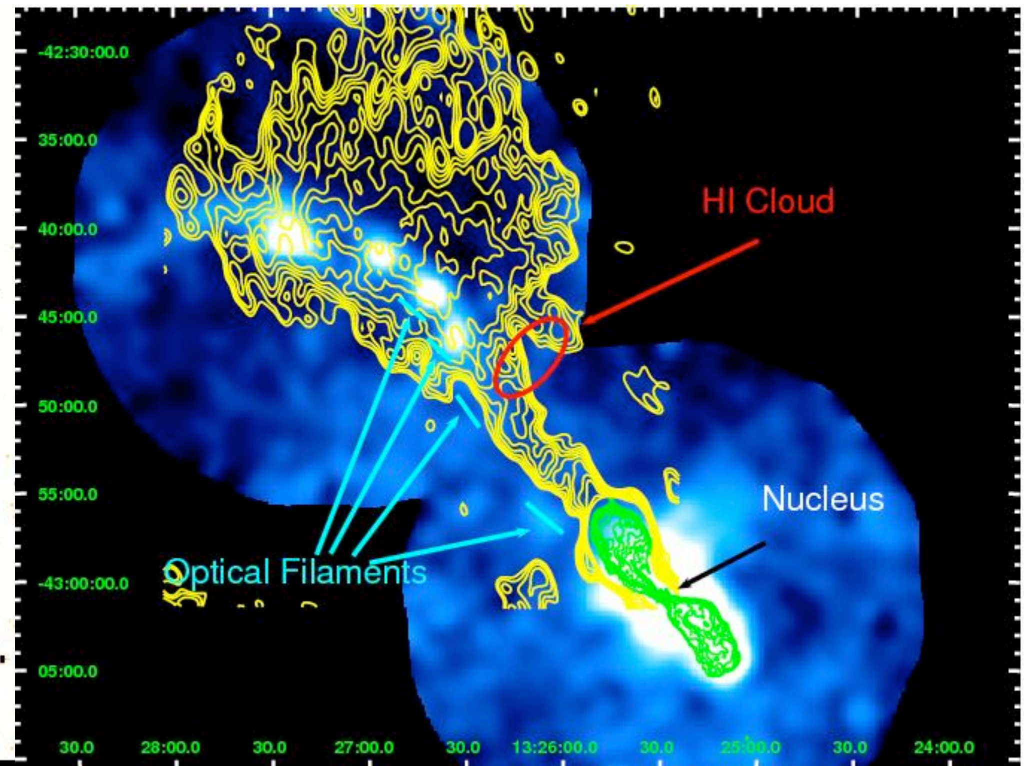
Chandra images of Cen A inner lobes with radio contours





Cen A lobes (inner and middle)



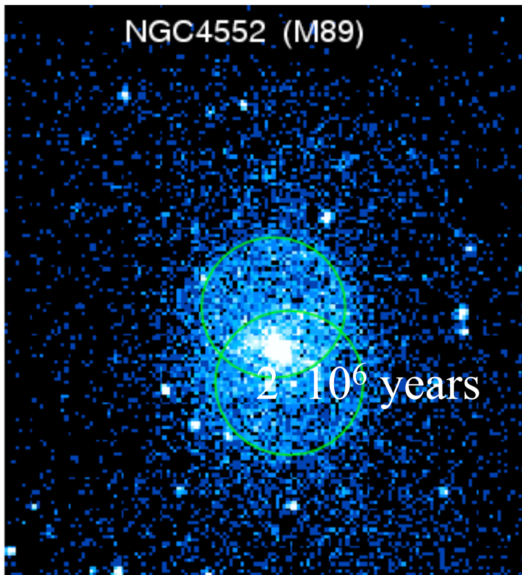


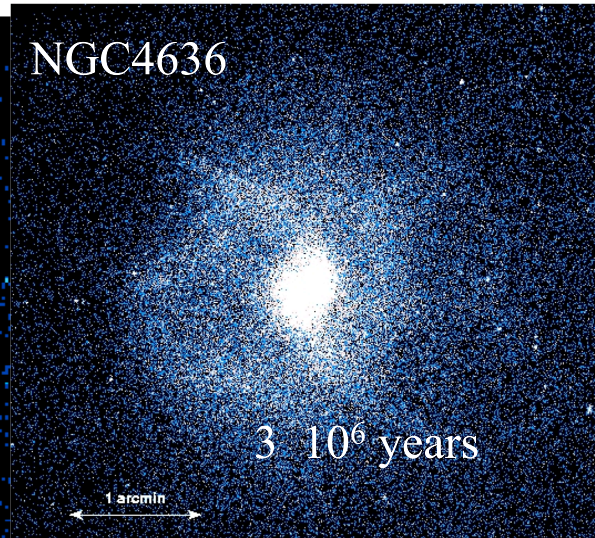
XMM image shows over-pressured X-ray regions in northern lobe. Northern inner lobe has “popped”. (Kraft et al. 2008)

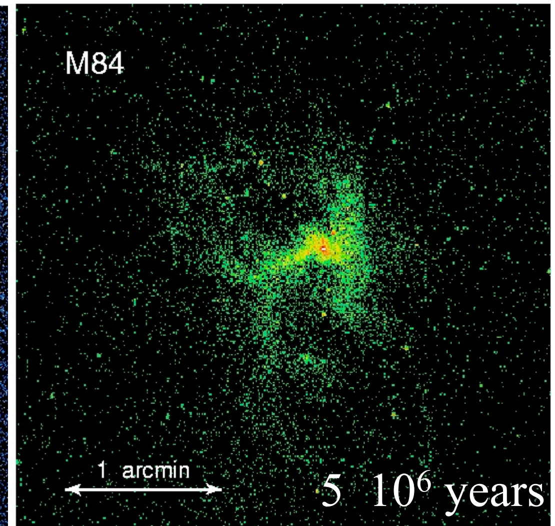
Examples of outbursts in early type galaxies -- ages 2 10^6 - 5 10^7 years

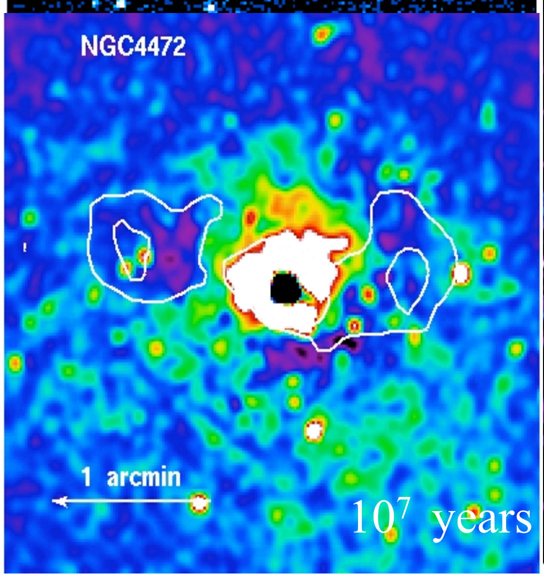
In galaxies most rims are cool. - few shocks.

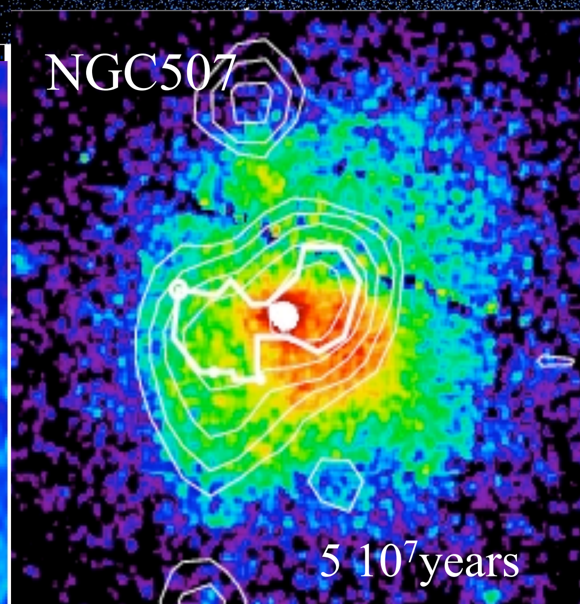
The rising bubbles are gently imparting energy to the gas (and dragging up cool material from the core).

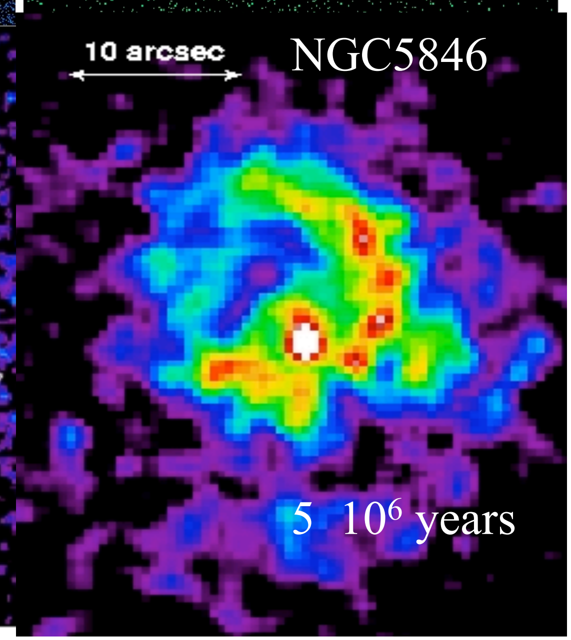




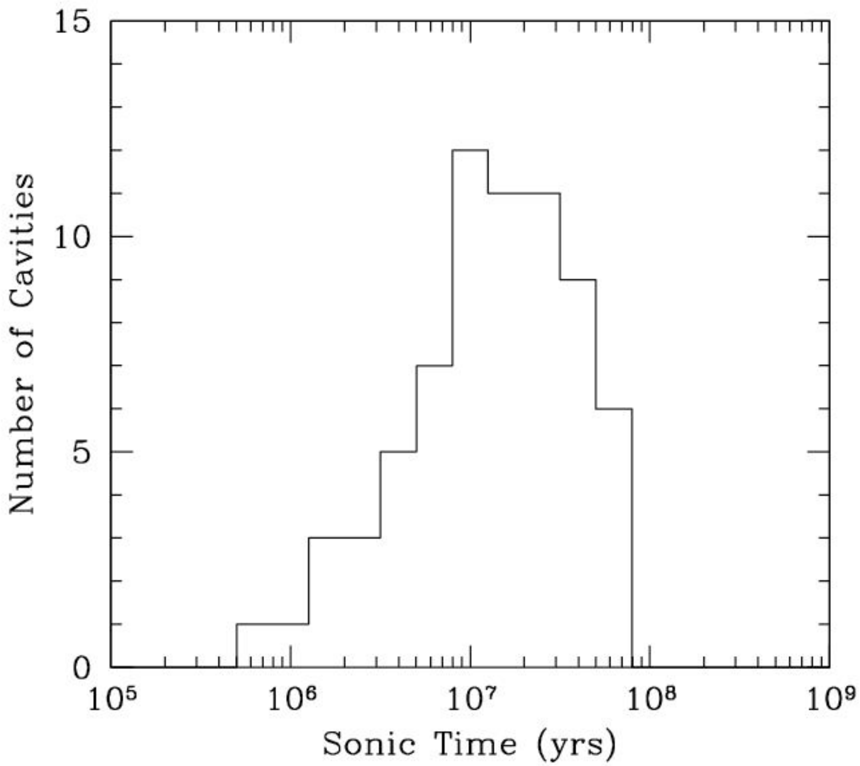


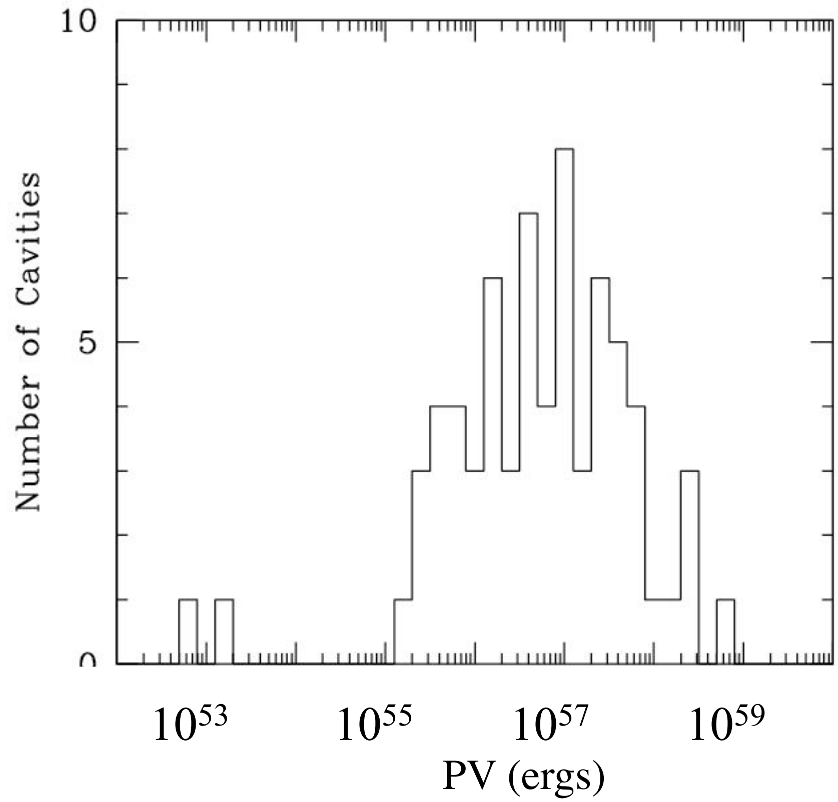






In galaxies, outbursts are recent (=> frequent) and impart significant energy to the ISM - enough to balance cooling



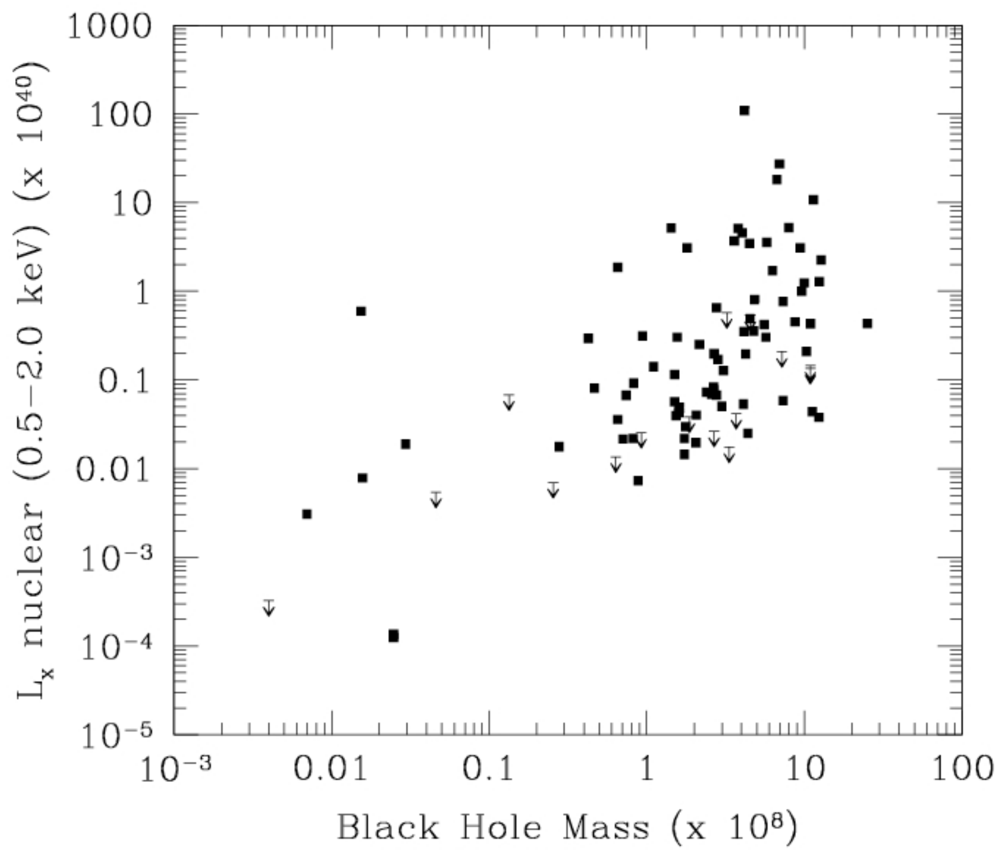


Ages and outburst energy for the 27 galaxies/groups with cavities (Nulsen, Jones, Forman, Churazov & friends)

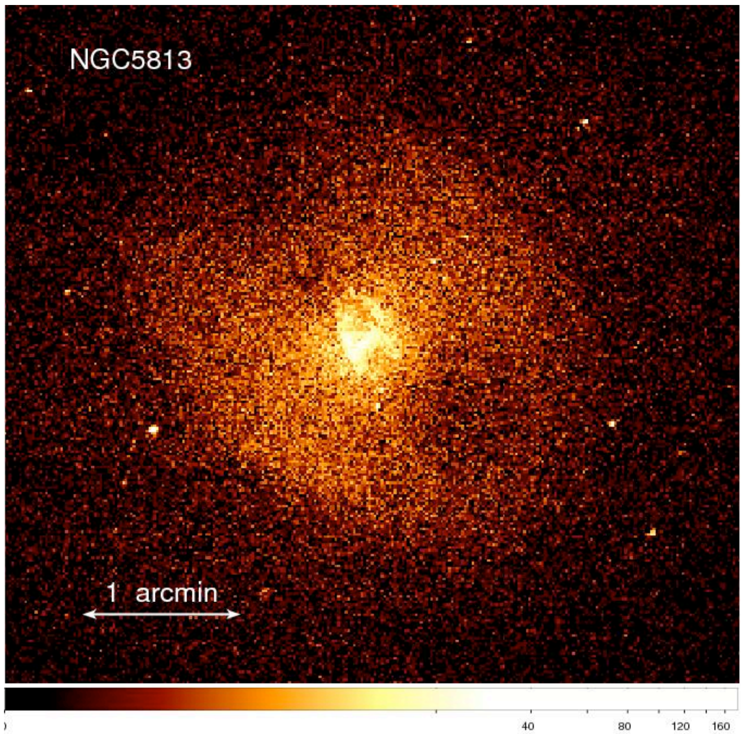
How common are AGN outbursts?
Determine fraction with nuclear X-ray emission

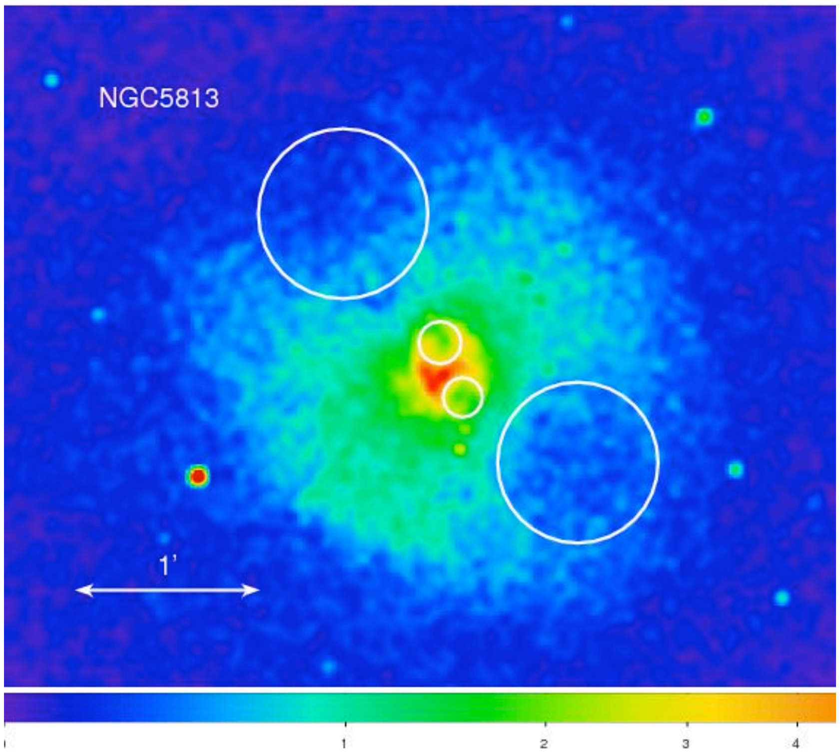
In "normal" early-type galaxies -

X-ray emission detected from the nucleus for ~80% of early-type galaxies from a sample of 160 galaxies (Jones et al. 2008)



Galaxies with multiple outbursts

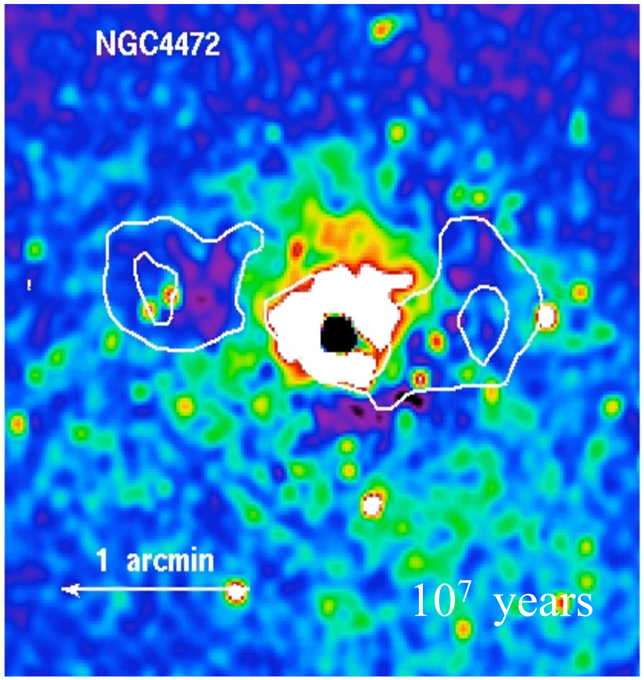




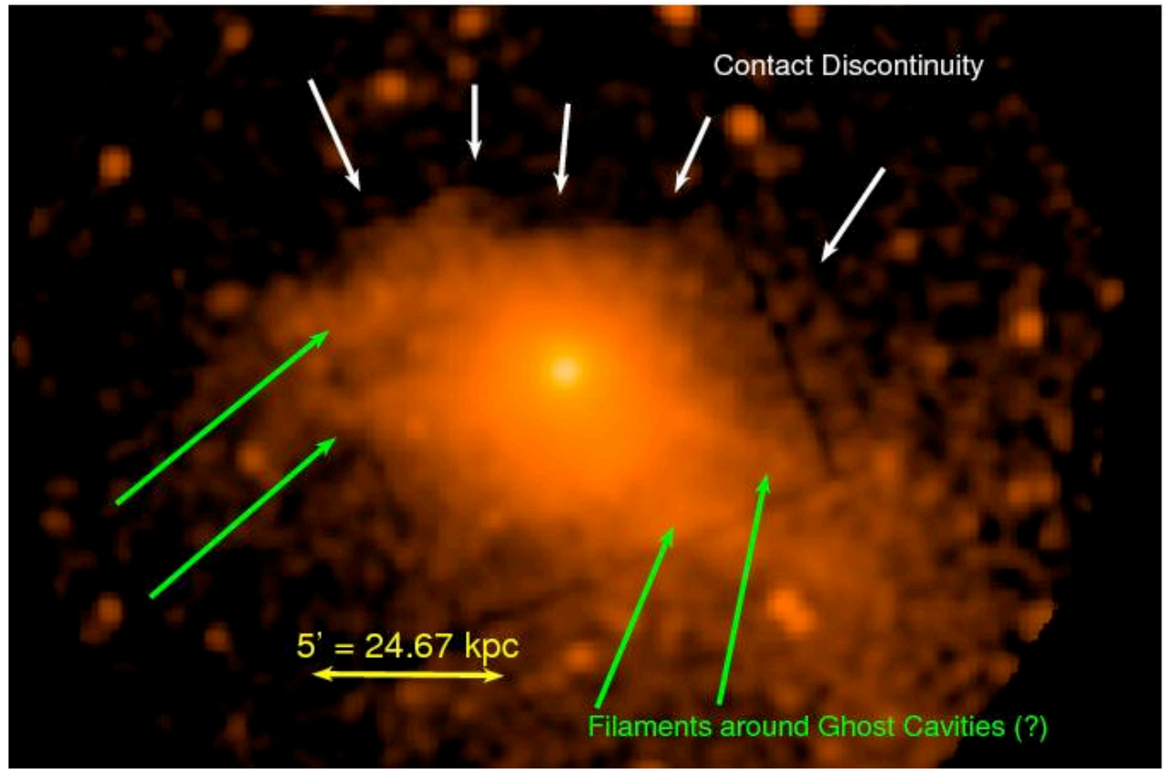
NGC5813 with Chandra (Forman et al. 2008)

Multiple outbursts in Cen A, M87

Multiple Outbursts in NGC4472

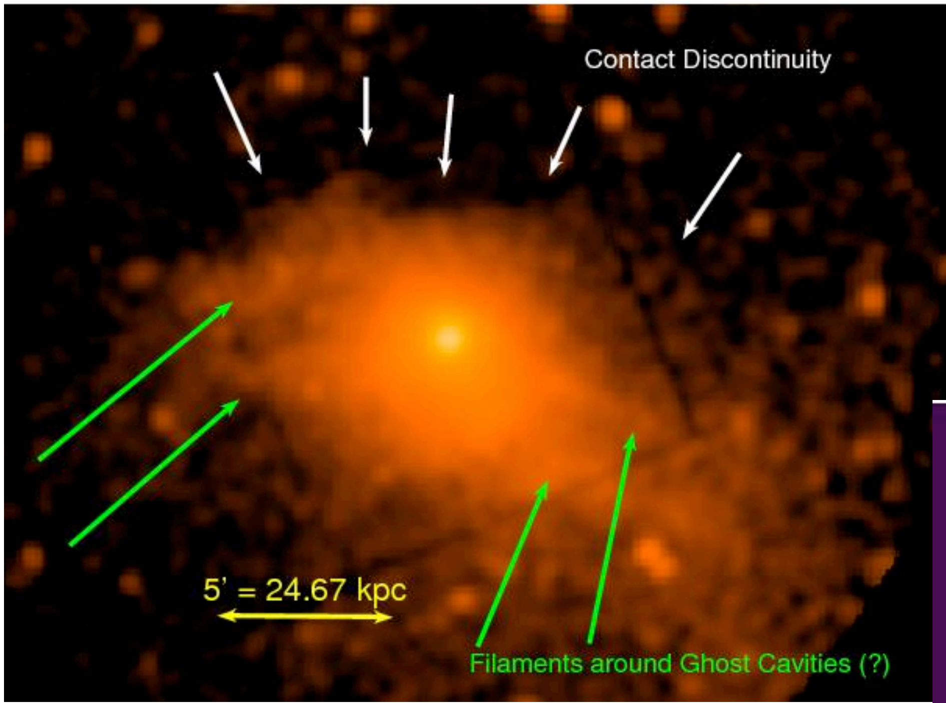


Chandra - inner bubbles
Biller et al.

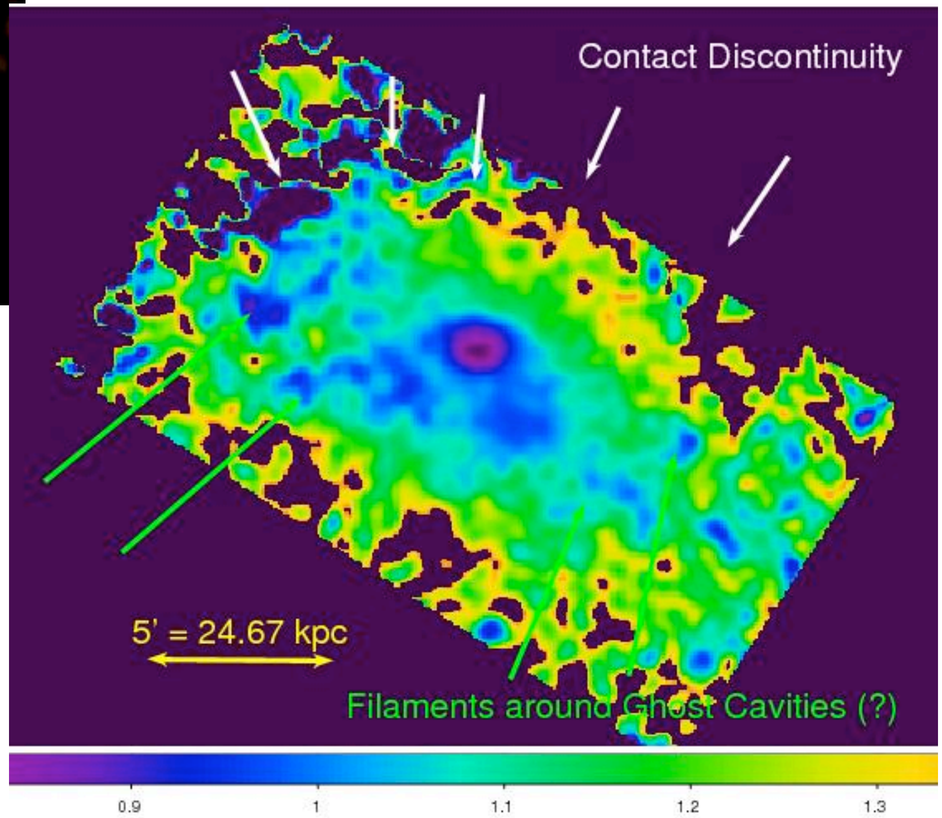


XMM - large outer bubbles
Kraft et al. 2008

XMM-Newton image of elliptical galaxy NGC4472



Rims of X-ray bubbles are cool



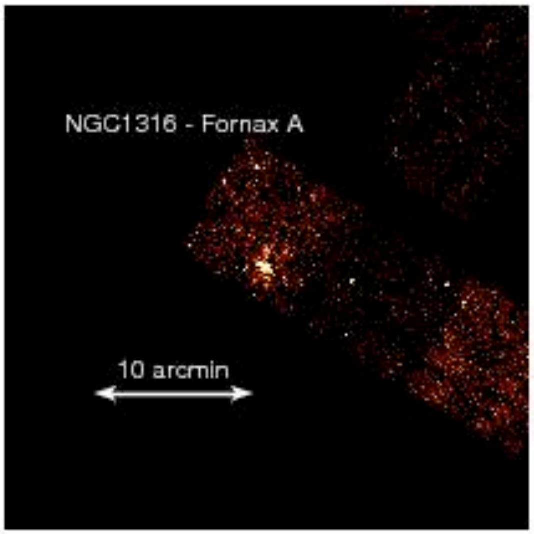
What are the impacts of the outbursts on the gas?

Enough energy to reheat the cooling gas? YES

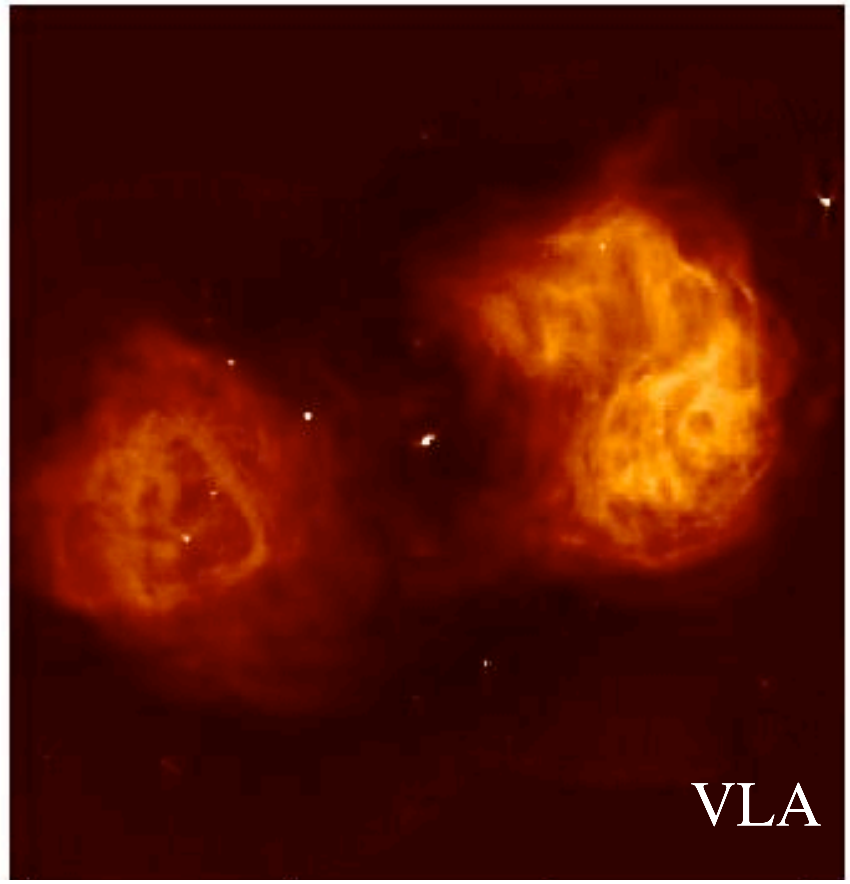
Enough energy to drive the gas from the galaxies?
Not usually, but…

Enough energy to provide non-thermal support to gas?
Not in small sample studied so far

Large AGN outbursts can remove gas from galaxies

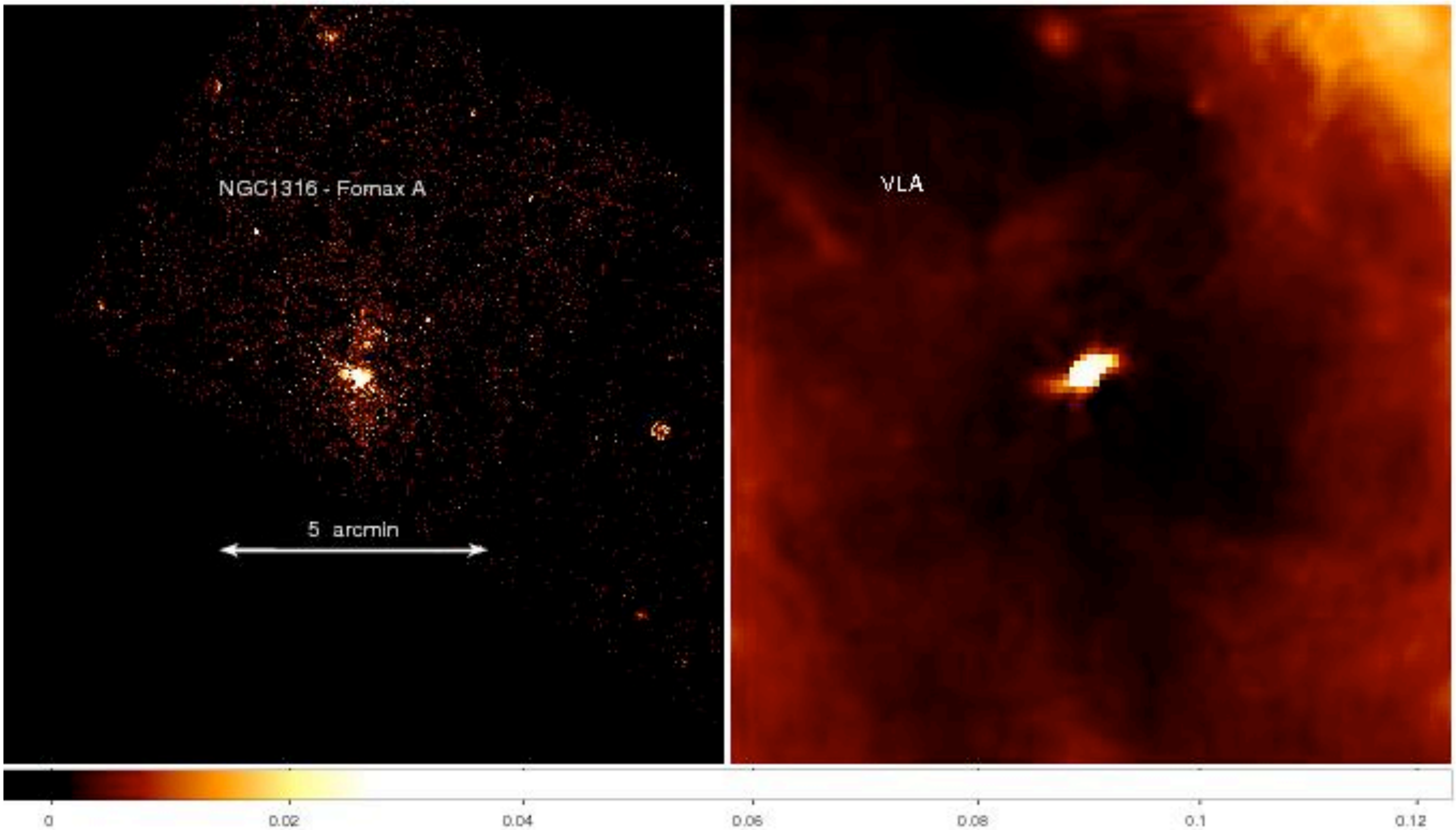


Chandra



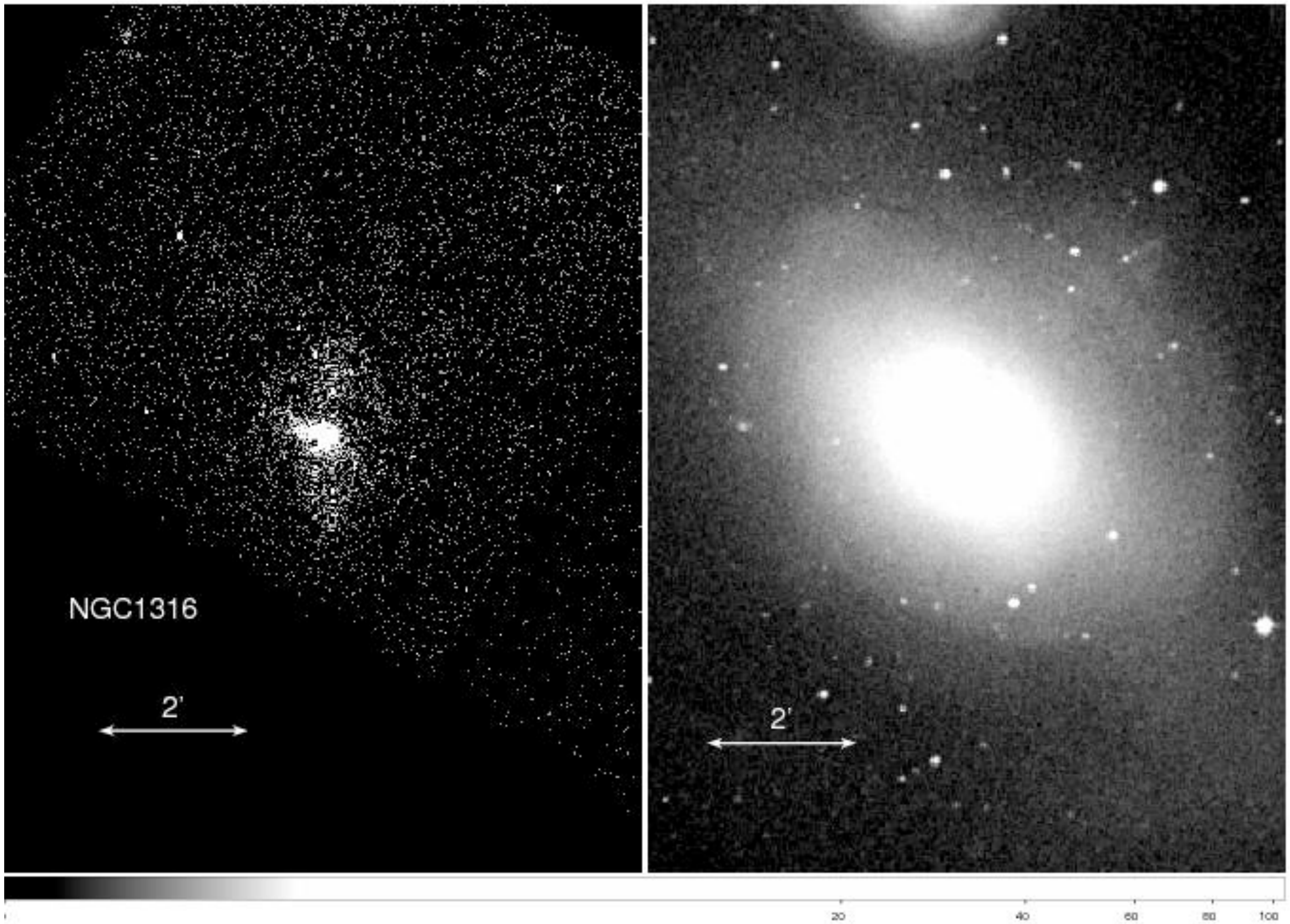
Example --- NGC1316 = Fornax A

AGN Outbursts that Remove Gas



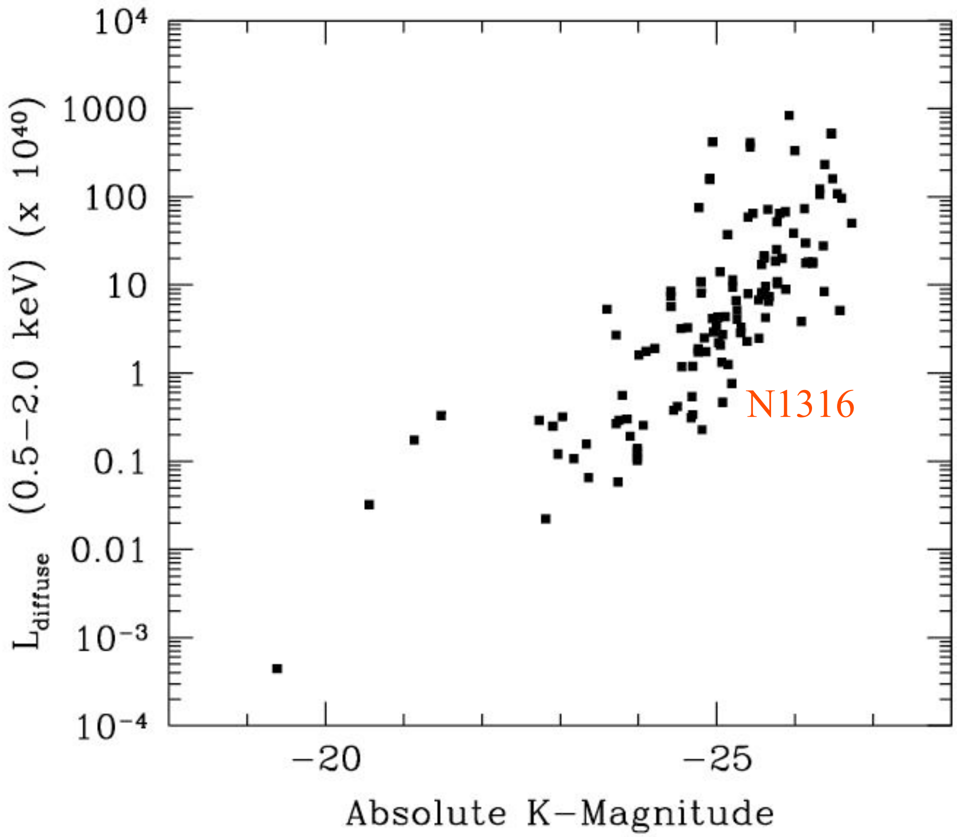
First example --- NGC1316 = Fornax A

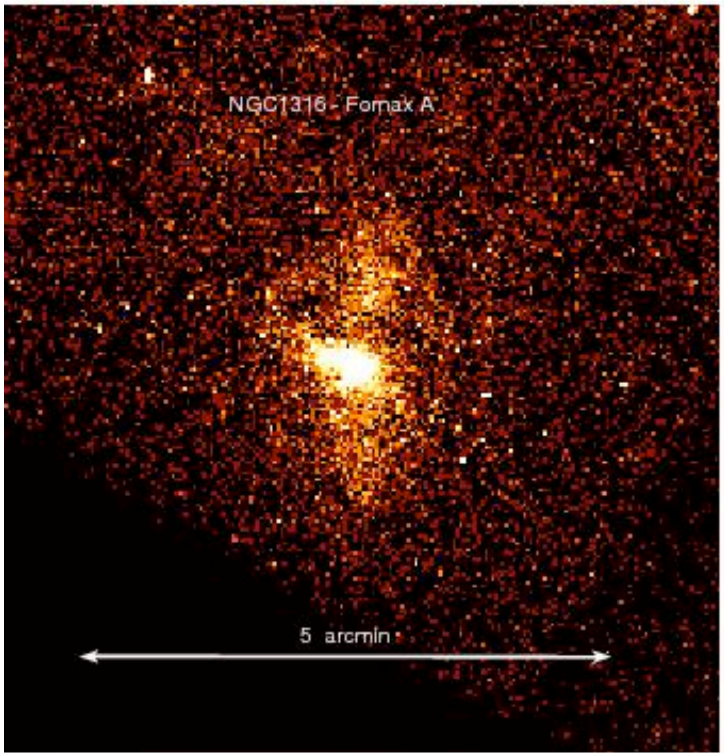
AGN Outbursts that Remove Gas



In N1316, X-ray gas is only in the galaxy core, not the halo.

AGN Outbursts that Remove Gas



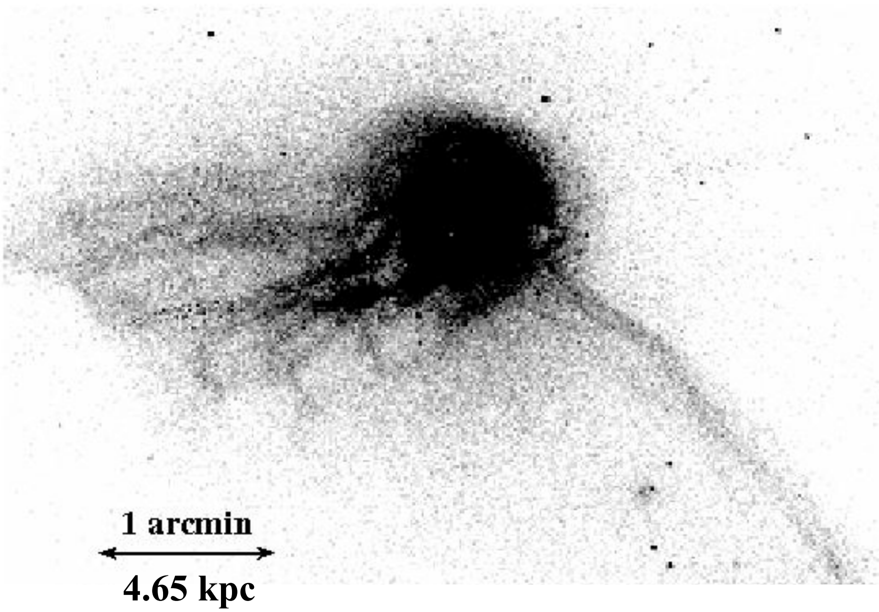


NGC1316 = Fornax A

Scatter in L_X-opt mag relation is partly due to gas removal and partly due to environment (galaxies in the centers of groups)

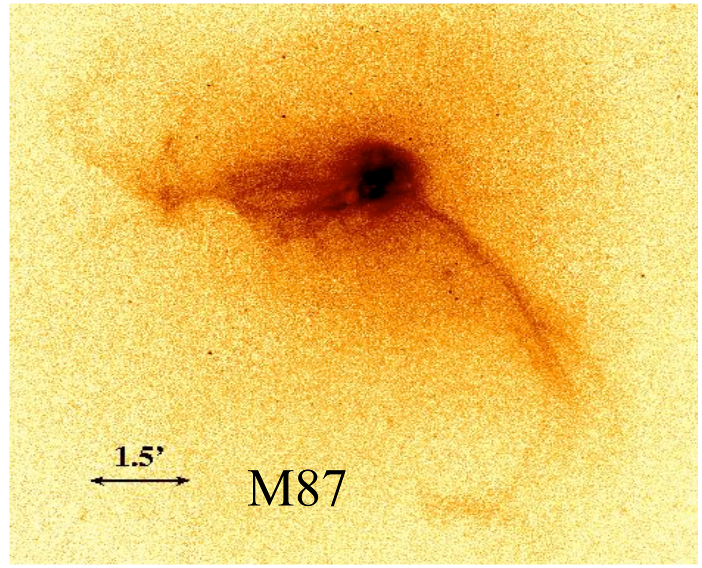
Do outbursts cause turbulence in the gas?

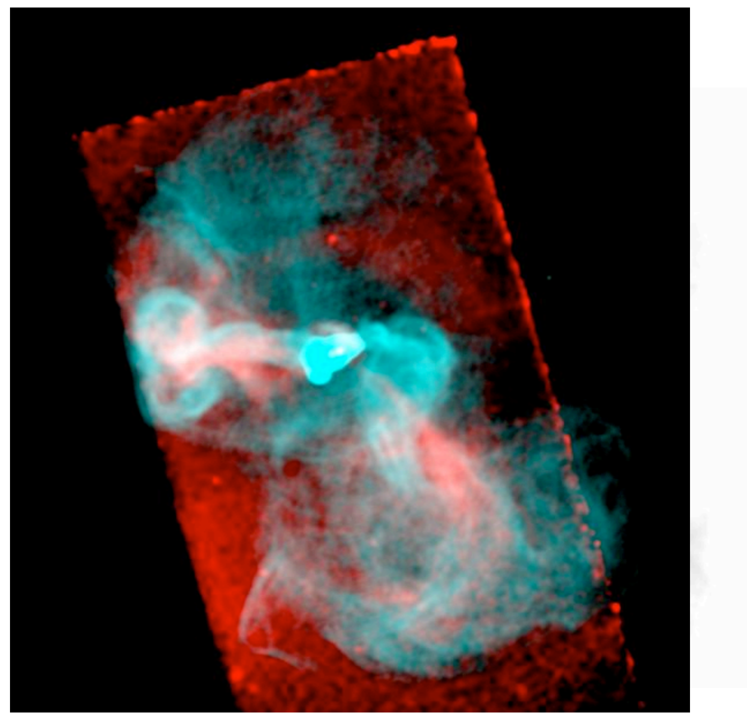
Is there non-thermal pressure support?



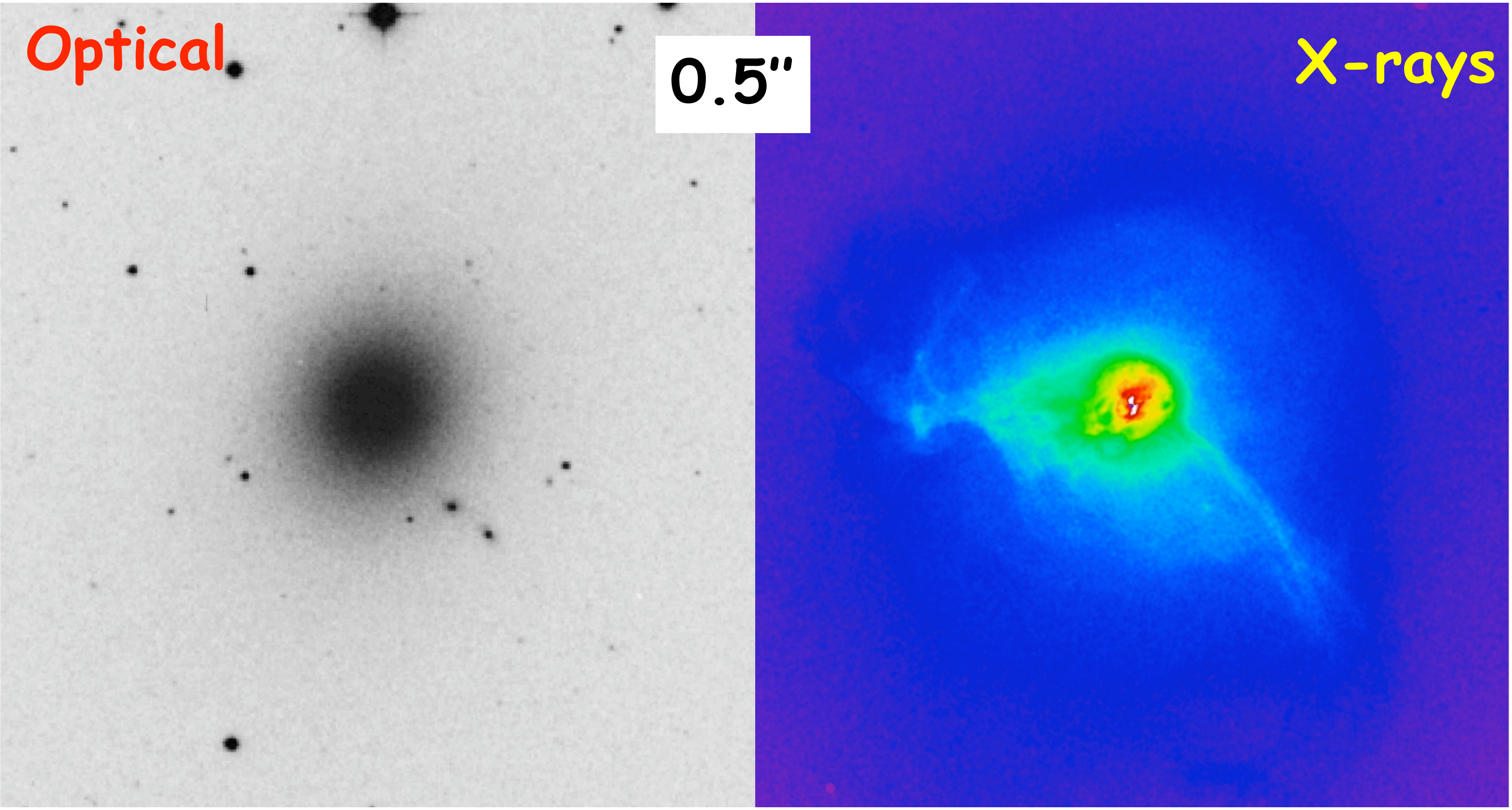
Eastern Arm - classical buoyant bubbles
Sequence of small buoyant bubbles
•PV $\sim 10^{54}$ - 10^{55} ergs

(M87 see Forman et al 2005, 2007)





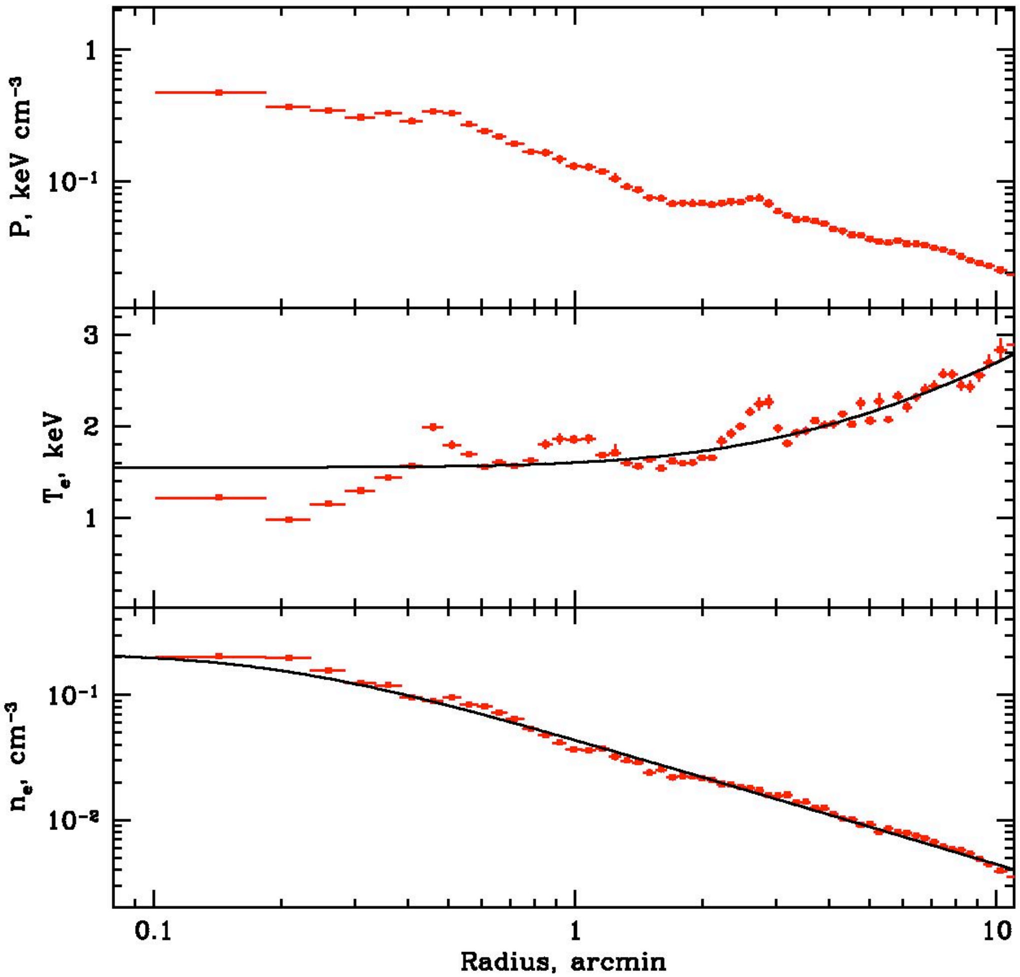
X-ray vs optical potential profiles (Churazov et al. arXiv0711.4686



Stars: gravity

Gas: gravity, cosmic rays, magnetic fields, turbulence

Deprojected X-ray data: gas temperature and density



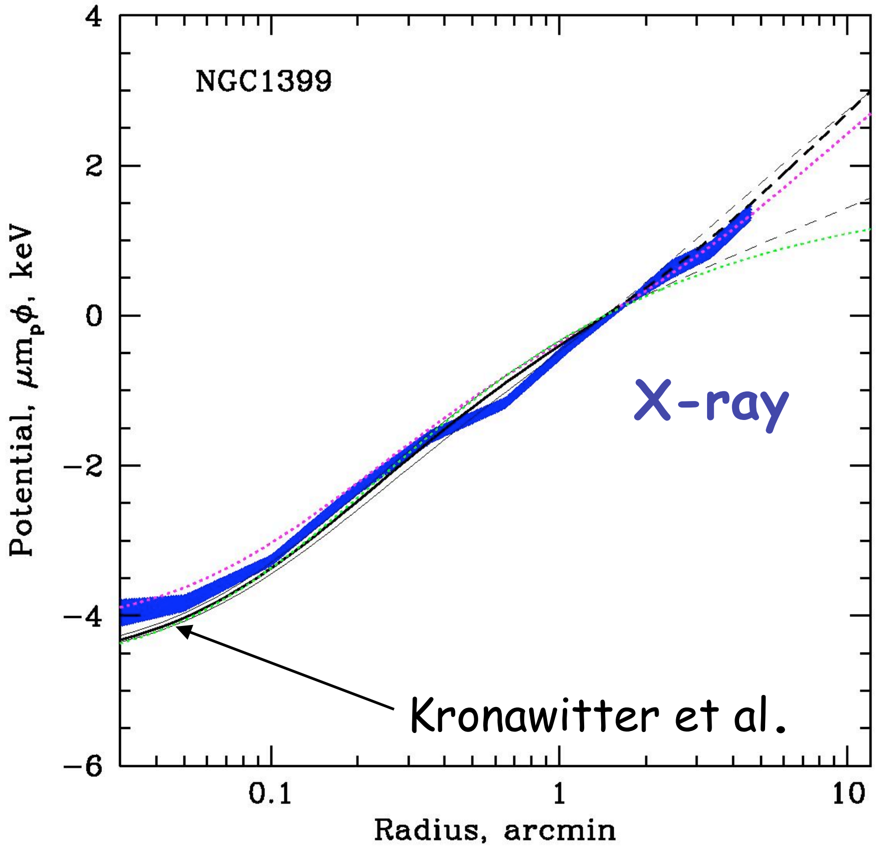
$$n_e(r), T_e(r) \quad P(r)$$

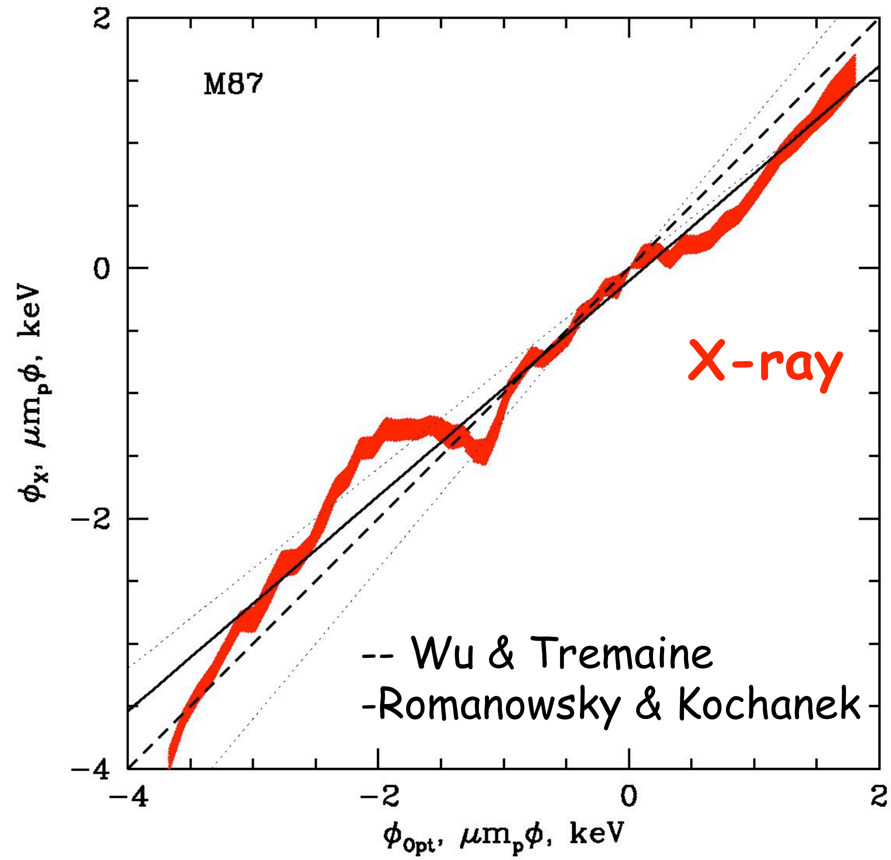
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\varphi}{dr}$$

$$\varphi = -\frac{k}{\mu m_p}\left[\int T_e \frac{d\ln n_e}{dr} dr + T_e\right] + C$$

Gravitational potential depends only on measured quantities -- temperature & gas density And hydrostatic equilibrium!



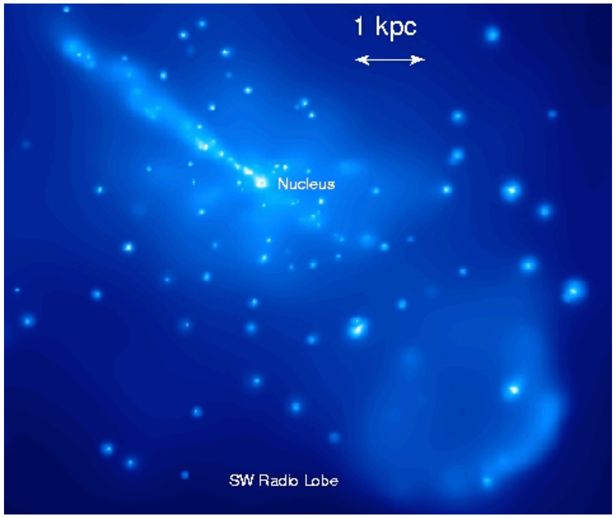


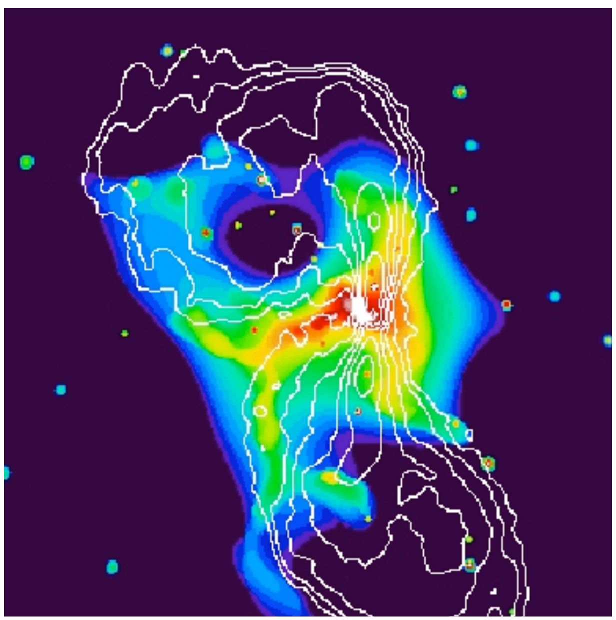
N1399 $$\varphi_X(r) \approx 0.93\varphi_{opt}(r)$$

M87 $$\varphi_X(r) \approx 0.85\varphi_{opt}(r)$$

At least in N1399 and M87, non-thermal pressure is not significant

Conclusions





Energy input from AGN is common in galaxies

- reheats cooling gas, can drive gas from their cores/ halos, and is important for galaxy evolution

In luminous ellipticals, ~30% have cavities => recent outbursts

- typical ages are 3 10^6 to 5 10^7 years
- typical outburst energies (estimated from cavity sizes) are 10^{55} to 10^{59} ergs

~80% of all early type galaxies have weak X-ray AGN

Several examples of multiple AGN outbursts (Cen A, N5813, N4472)

But (based on small sample), non-thermal pressure support appears to be small (< 15%)